REPORT

Review of the United States Environmental Protection Agency DRAFT Report Entitled "Investigation of Ground Water Contamination near Pavillion, Wyoming"

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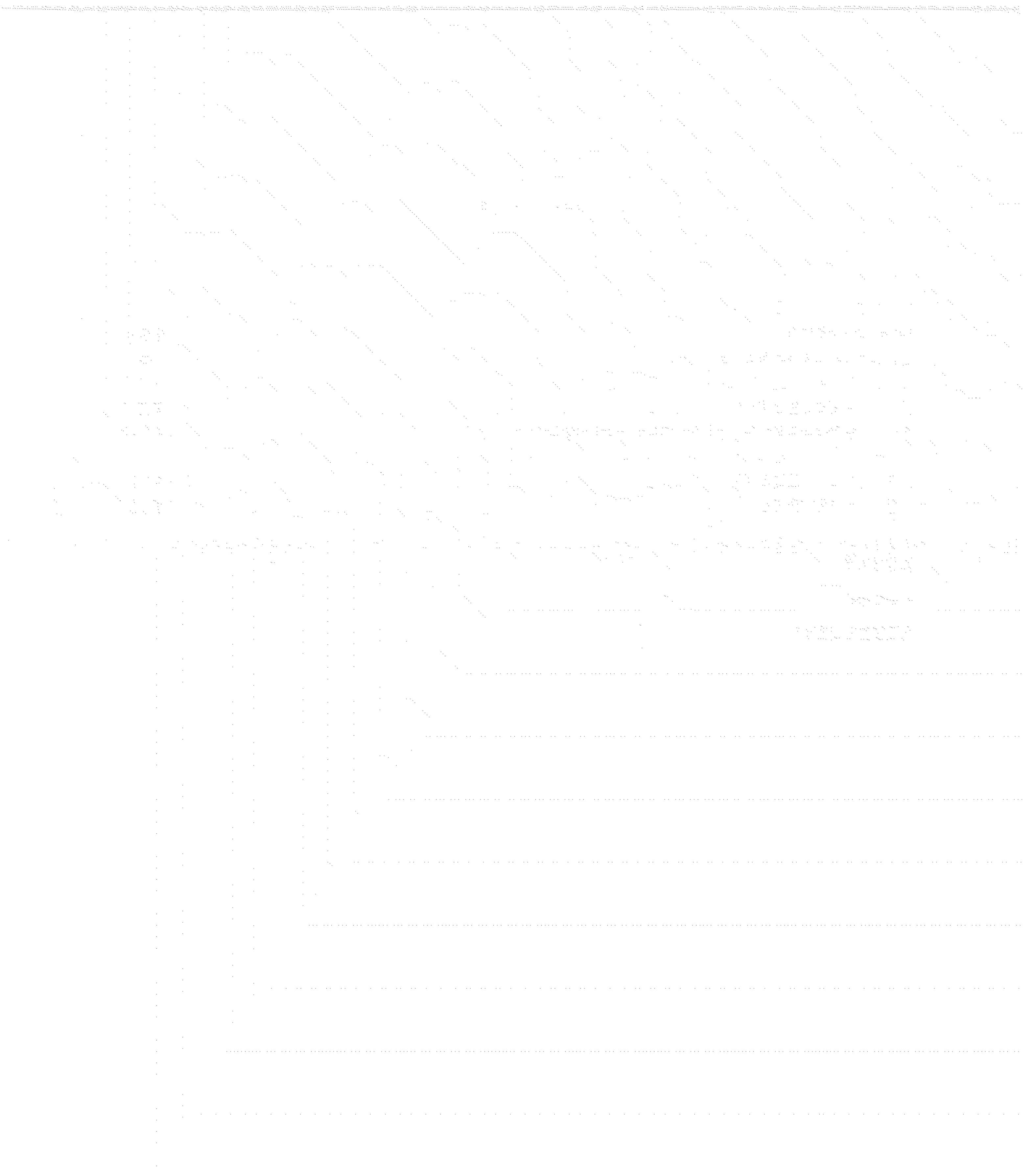

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1.0 INTRODUCTION

This report is prepared in connection with the United States Environmental Protection Agency's (USEPA) investigations of groundwater quality in a rural area east of the town of Pavillion, Wyoming. USEPA's investigations resulted in their issuing a draft report entitled, "Investigation of Ground Water Contamination near Pavillion, Wyoming" (Draft Report) (USEPA, 2011b). My report addresses certain aspects of the Draft Report, dealing primarily with the geology and hydrogeology of the Pavillion Gas Field along with some of USEPA's field investigations.

My name is Robert J. Sterrett and I am employed as a hydrogeologist with the firm of Itasca Denver, Inc. (Itasca). Itasca is located at 143 Union Boulevard, Suite 525, Lakewood, Colorado 80228. I have worked as a hydrogeologist since 1974. I earned a Bachelor of Science degree in geology (with honors) from Indiana University, Bloomington, Indiana; a Masters of Science degree in water resources management; and a Masters of Science degree in geology and geophysics (emphasis on hydrogeology) from the University of Wisconsin, Madison, Wisconsin. I received my Ph.D. in geology and geophysics (emphasis on hydrogeology and engineering geology) from the University of Wisconsin, Madison, Wisconsin. I have over 30 years of experience in the field of hydrogeology and contaminant transport. I specialize in groundwater flow-system analysis, vadose-zone transport studies, soil and groundwater remediation, mining hydrogeology and hydrogeology issues associated with oil and gas operations. Since 1981, I have worked on over 200 waste sites in the United States and overseas. My work has involved site investigation, remediation design, and evaluation of remediation systems that have been installed for soil and groundwater, as well as mine dewatering issues. In 2007, I was the technical editor of and a contributor to the Third Edition of Groundwater and Wells, a standard reference text for the water-well industry. A copy of my résumé is provided as Attachment RJS-1.

2.0 BACKGROUND

In its Draft Report, the USEPA reaches conclusions relating to impacts to groundwater quality as the result of a technique that is used by the oil and gas industry to stimulate production from oil and gas reservoirs that do not readily transmit these resources. This stimulation technique is called hydraulic fracturing or "hydro frac or fracking."

The USEPA responded to complaints by domestic well owners in the Pavillion Field area that water from their wells had objectionable taste, color, and odor problems. The stated objective of USEPA's investigation was to determine the presence, not extent, of groundwater-quality impacts to the water-bearing zones from which domestic water supplies are obtained. In addition, the USEPA wanted to differentiate, if possible, shallow sources of chemical constituents such as production pits, septic systems, and agricultural/domestic practice from deeper source terms (gas production wells).

The USEPA had the following secondary objectives for their study:

- Installing and sampling two deep monitoring wells in two areas where groundwater-quality impacts were suspected.
- Conducting a soil-gas survey to detect the migration of gases from deep subsurface media.
- Developing a sampling methodology that allows collection of groundwater samples at depths of approximately 1,000 feet (ft) below ground surface (bgs) while retaining dissolved gases.
- Improving quality control associated with soil-gas sampling.

The USEPA conducted four sampling events that involved the collection and analysis of groundwater samples from various domestic, stock, select monitoring, and municipal wells (two of the five Town of Pavillion wells). Soil samples were also collected near the perimeter of production pits. The USEPA also conducted soil-gas sampling.

With these objectives the USEPA is remiss in not reporting the data from soil-gas sampling. Data from this sampling effort were not included in the Draft Report.

The USEPA installed two groundwater monitoring wells (MW01 and MW02) that, according to the USEPA, were located away from gas production wells, known locations of pits, and areas of domestic waste disposal (USEPA, 2011b), but in two areas where groundwater-quality impacts were suspected. One well was screened from 765 to 785 ft bgs, and the other from 960 to 980 ft bgs. The goal for the depths of the wells was to screen monitoring wells in white coarse-grained sandstone that, according to the USEPA, is supposed to exist at a depth of 800 to 1,000 ft bgs in the Pavillion Field (USEPA, 2011a). This sandstone, according to the USEPA, is supposedly targeted by local well drillers for domestic well installation (USEPA, 2011b); however, most domestic wells in the Pavillion Field area are less than 500 ft deep. As will be discussed in my report, the installation, completion, and development techniques for USEPA's monitoring wells are highly suspect, rendering the analysis of water samples not representative of groundwater conditions.

3.0 SUMMARY OF QUESTIONS AND ANSWERS

This report will discuss three separate geographic areas of my analysis. The first is the Wind River Basin and the general area of the Pavillion Field. My discussion on this larger area is focused primarily on overall geologic conditions. The location of the Wind River Basin is shown in Figure RJS-1. The second area of discussion is the Pavillion Gas Field or what I will reference as the Pavillion Field in this report. The location of the Pavillion Field in relation to the boundaries of the Wind River Basin is shown in Figure RJS-1. An area of more intense investigation is shown in Figure RJS-2. Figure RJS-2 is comprised of eight sections (each a square mile in area) where most of the gas production wells, the two USEPA monitoring wells, four former production pits that are being investigated by Encana, and many of the domestic/stock wells that were sampled by USEPA are located. This area will be referenced as the core area for purposes of this report.

The eight sections of the core area (Figure RJS-2) are located in Township 3 North, Range 2 East, and the sections of interest are 1 through 4 and 9 through 12. I have been asked to address the following questions related to the hydrogeologic conditions in the Pavillion Field along with questions relating to well installation, completion, and sampling. These questions are:

- What is the naturally occurring groundwater quality of the water-bearing units of the Wind River Formation?
- What are the horizontal and vertical directions of groundwater flow in the approximately upper 800 ft of the Wind River Formation in the core area shown in Figure RJS-2?
- Will groundwater pumping from individual domestic wells impact groundwater flow directions in the Pavillion Field area?
- Are any public drinking water wells threatened?
- Are the former production pit areas potential sources of "groundwater contamination" that result in what the USEPA describes as "plumes of unknown extent?"
- Did the USEPA and their contractors properly install, complete, and develop their two groundwater monitoring wells so that groundwater samples collected from them accurately represent ambient conditions of the water-bearing zones?

Based on my knowledge of the Wind River Basin, the Pavillion Field, the surrounding areas, and my technical expertise, I have reached the following answers to the respective questions stated above. Detailed support for these answers is provided later in this report.

- Groundwater quality in the Wind River Basin, the Pavillion Field, and the core area is highly variable due to the anisotropic nature of the geologic units. The sand lenses that are tapped by domestic water wells are discontinuous and the discontinuous nature of the lenses leads to variability in water quality. In the Wind River Formation, the primary constituents that naturally influence the quality of groundwater in the area are sodium, sulfate, and total dissolved solids (TDS). The TDS of the groundwater from shallow wells in the study area (wells less than 800 ft deep) varies from approximately 200 to over 5,000 mg/L. The secondary drinking-water standard for TDS is 500 mg/L. High TDS water has an objectionable taste. A discussion of secondary standards will be provided later in this report. The sulfate concentrations of the water vary from approximately 12 to 3,600 mg/L. The secondary drinking-water standard for sulfate is 250 mg/L. Sulfate in elevated concentrations (above 250 mg/L) in water also has an objectionable taste. Sodium varies from 40 to 1,200 mg/L. There is no drinking-water standard for sodium; however, dissolved minerals, in total, lead to objectionable taste in most waters in the Pavillion Field. Poor groundwater-quality conditions in the Wind River Formation in the Wind River Basin and the Pavillion Field are from the minerals that occur in the geologic materials. The minerals are leached by percolating waters.
- The overall horizontal direction of groundwater flow in shallow (approximately top 50 ft of saturated zone) water-bearing zones is towards the southeast in the core area (Figure RJS-2). Groundwater elevation data from existing groundwater monitoring wells, including USEPA's monitoring wells in the core area, indicate that the general vertical direction of groundwater flow is downward from shallow water-bearing zones to deeper groundwater. There is one well completed in the Wind River Formation in the core area that is under artesian, flowing conditions, but this situation is rare. The hydraulic gradient within the gas producing section of the Wind River Formation in the core area and in the Pavillion Field generally follows a normal hydrostatic gradient, contrary to the Draft Report's assertion of an upward flow gradient or an unknown flow gradient. A downward hydraulic gradient means that chemicals at depth cannot migrate upward. Pressure transients induced by hydraulic fracturing are of such short duration that chemical transport is governed more by the long-term hydraulic gradients that are downward.
- Pumping from an individual domestic well in the core area does not have a significant impact on groundwater flow directions, and the radius of the zone of capture exerted by a well is likely less than 100 ft. This limited zone of capture is

primarily due to the low pumping rates (average of less than 1 gpm) from individual wells.

- The core area that comprises the eight sections shown in Figure RJS-2 does not contain any public drinking water wells. Individual households use wells for domestic use or stock watering. The municipal wells for the Town of Pavillion are upgradient of the core area (a distance of approximately 1.5 miles) and are not impacted by Pavillion Field-related water-quality concerns.

- Encana has studied 33 former production pits in the Pavillion Field area. Encana identified four historical pit areas associated with impacted groundwater, and Encana is working with the State of Wyoming Department of Environmental Quality (WDEQ) to address these pits. As part of their investigations, Encana has assessed the extents of groundwater impacts at three of the four sites. At three of the sites, the investigative work to date confirms that no domestic wells have been impacted; at the fourth site, preliminary field work to assess extents has been initiated; however, based upon information from the three other sites, the extent of groundwater impacts is also expected to be limited, with no impact to any domestic wells. In summary, former pits are not a significant source or threat to groundwater quality in the Pavillion Field.

- The USEPA did not properly install, complete, and develop their two groundwater monitoring wells. As such, the analyses of water samples collected from both monitoring wells do not accurately represent ambient conditions of the water-bearing zones and cannot support decision making.

The basis for each of these answers is provided in Section 5.0 of this report.

4.0 REGIONAL AND STUDY AREA HYDROGEOLOGY

The Pavillion Field is underlain with three different geologic units that are pertinent to this study. From land surface downward the three units are:

- Quaternary deposits consisting of alluvium and colluvium,
- Wind River Formation (in some parts of the Pavillion Field this formation is at land surface), and
- Fort Union Formation.

The Pavillion Field is located in the western third of the Wind River Basin which is a large, deep sedimentary basin that is located in central Wyoming (Figure RJS-1). The sediments in this basin reach thicknesses of over 25,000 ft and consist of several different geologic units. As will be described below, the Wind River and Fort Union Formations are the reservoirs for gas production in the Pavillion Field.

The Fort Union and Wind River Formations consist of a very large wedge of fluvial (deposited by streams) and lacustrine (lake sediments) deposits that accumulated in the Wind River Basin during deformation that occurred in Paleocene and early Eocene times between 40 and 65 million years ago (Keefer, 1969). This wedge can be up to 6,000 ft thick in the Pavillion Field. The deposition of the Fort Union and Wind River Formations coincided with a period of active subsidence of the Wind River Basin and pronounced uplift and rapid erosion of the surrounding uplands (Keefer, 1969). The sedimentary sequences vary greatly in thickness and lithology from one place to another due to depositional processes. Both formations are relatively coarse-grained (e.g., sands and gravels) and thinly bedded near their outcrops[1] located adjacent to the surrounding mountains, but become predominately thicker and more fine-grained (e.g., silt and clays) just a few miles downdip from the outcrops (Keefer, 1969).

In the central and northeastern parts of the Wind River Basin, the Waltman Shale Member of the Fort Union Formation is present (Figure RJS-3). This shale is of lacustrine origin and its

[1] Outcrop is an area where the geologic unit is exposed at land surface.

presence is important as a caprock that limits the upward migration of gas, hydrocarbons, and other fluids due to its low permeability. Shales are rock units consisting of clay-size particles that have been consolidated under pressure and heat to create rock. The Waltman Shale is not present in the Pavillion Field area as shown in Figure RJS-3. As discussed below, the absence of a wide-spread, thick shale does not prevent the upward migration of gas through diffusion (a process that will be explained later), which is why gas is prevalent at shallow depths (less than 800 ft) in the Pavillion Field.

The lithologies within the Wind River Formation are extremely variable, both laterally and vertically. This variability is due to the depositional processes that created the formation. The fine-grained, basinward units of the formation are primarily claystone, shale, siltstone and sandstone, and only minor amounts of conglomerate. Many of the sandstone beds are elongate, highly lenticular bodies. The sandstone bodies or lenses within the Wind River and Fort Union Formations have a typical aspect ratio of 8 or 10 to 1 (Robinson and McCabe, 1997). This aspect ratio means that a sandstone lense 10 ft thick would be approximately 80 to 100 ft wide. The sandstone lense would then be surrounded by low-permeability shales or claystones. The uppermost strata are moderately bentonitic (a type of clay) and tuffaceous. The presence of clays in the sandstones reduces the permeability of these units. The upper portions of the Wind River Formation are classified as a fine-grained sequence (e.g., consists of clay and silt) (Figure RJS-4) (McGreevy et. al., 1969). The fine-grained nature of these deposits means that they are not capable of transmitting large volumes of water.

The Pavillion Field gas is produced in multiple sandstone reservoirs within the Wind River Formation and the Upper Fort Union Formation at depths ranging from 1,500 to 5,000 ft below ground surface (bgs) (Bjorklund, 1978). Gas accumulation in these reservoirs is localized by stratigraphic variation on the crest and flanks of a broad structural dome. This dome, in top view, is shown in Figure RJS-5, and the crest is more than 3,000 ft bgs.

The precise geometries of sandstone reservoir bodies in the Wind River and Fort Union Formations are not known because of difficultly correlating individual sandstone units that are

of limited lateral extent, and well spacing (from which geologic information is obtained) is not close. We do know that the lateral extent in feet is approximately ten times the thickness and that the concept of broad continuous sandstone layers is not correct. Only one sandstone layer, the basal sandstone in the Wind River Formation, can be mapped as a discrete unit over a significant distance. It contains up to approximately 50 ft of a gas-producing section on the south flank of the field and pinches out to the north across the crestal portion of the structure (Bjorklund, 1978). Figure RJS-6 is a cross section that shows the basal sandstone unit, and this unit is encountered at a depth of more than 3,000 ft bgs in the Pavillion Field.

Figure 20 of the USEPA Draft Report (see Figure RJS-7 of my report) depicts there are thick, continuous sandstone layers throughout the core area especially at shallow depth. This is not the case. The quality of this figure in the Draft Report is poor, and how the correlations are derived is unknown. The geologic model shown by the USEPA in their Draft Report is counter to geologic interpretations provided by geologists working for the USGS and industry. Figure RJS-8 shows the location of USEPA's cross section superimposed upon a structural contour map of the top of the Fort Union Formation. The structural contour map has been modified from that provided by Bjorklund (1978) (Figure RJS-5) by the addition of faults. The locations of these faults have been interpreted based on additional information since Bjorklund's paper in 1978.

Figure RJS-9 is a revised cross section A–A'. In this cross section the same wells are used as those by the USEPA; however, the results of various geophysical logs have been displayed. In the Pavillion Field the Wind River Formation is approximately 3,400 ft thick. This formation is further divided into two members; a thick lower unit termed the Lysite Member and a thinner upper unit referenced as the Lost Cabin Member. The Lysite Member is the gas producing interval in the Pavillion Field. Figure RJS-9 shows the tops of perforations for the production wells included on the cross section. Porous zones in sandstone units other than the basal sandstone are limited in thickness and, in order to obtain economical quantities of gas, multiple zones may be perforated in a single well.

The average porosity[2] and permeability[3] of producing zones are estimated at 14 to 16 percent and 3 millidarcies (approximately 3 x 10^{-6} cm/s under standard pressure and temperature). These values may range to as high as 30 percent and 300 millidarcies (Bjorklund, 1978). The Lysite Member is characterized as a claystone sequence, interbedded with thin lenticular sands and silts representative of floodplain sediments. Individual sandstones vary from less than 10 to approximately 30 ft thick. Production well logs within the Pavillion Field (recorded on 20-acre spacings) rarely have sands that can be correlated between several boreholes. Examination of three-dimensional seismic data by Encana geophysicists/geologists and depositional analogs indicate that a sand lens 20 ft thick in the Lysite Member represents a channel that will have a width of only a few hundred feet and a limited length as well.

The gamma logs (the logs on the left side of the production well boreholes) have been used by Encana geologists for stratigraphic/lithologic identification purposes. Yellow coloration on the gamma logs indicates a sandstone lens; whereas, layers shaded green to dark purple are indicative of siltstones and claystones (finer-grained geologic materials). The induction resistivity logs (noted on the right side of the boreholes) provide information on rock type as well as fluid content and composition. Highly resistive zones (indicated by large deflections to the right) suggest sandstones containing water with low TDS or hydrocarbons. Shale units or zones containing water with high TDS will display low resistance.

The Lost Cabin Member in the Pavillion Field is approximately 800 ft thick and domestic water wells are completed in this member. The demarcation between the Lost Cabin and Lysite Members is transitional over a few tens of feet but the two members are distinguished primarily by porosity, lithology, and water quality.

[2] Porosity is the amount of open space within a specified volume of geologic material. It is defined as the volume of voids (open spaces) per total unit volume of geologic material. Porosity usually is expressed as a percentage of the bulk volume of the material.

[3] Permeability of a geologic material is its ability to transmit a fluid and is a measurement of how the pore spaces are interconnected.

The sandstone lenses within the Lost Cabin Member generally have porosities in the range of 24 percent; whereas, sandstone lenses in the Lysite Member have porosities in the range of 14 to 16 percent. This reduction in porosity is probably due to diagenesis.[4]

The lithology within the Lysite Member is finer-grained than the Lost Cabin, as denoted by the abundance of shale and claystone on the gamma logs in Figure RJS-9. As shown in Figure RJS-9, sandstone units within the Lost Cabin appear to be thicker and, in some instances, can be correlated; however, based upon water-level and water-quality differences in water wells screened within the Lost Cabin, the sand lenses do not appear to be correlated over long distances. Water levels and groundwater quality are discussed later.

Water quality within the Lysite Member is generally of lower quality than the Lost Cabin, however, the water quality within the Lost Cabin, as will be discussed later, is poor. Waters within the Lysite Member generally have TDS exceeding 10,000 mg/L and chloride concentrations greater than wells screened in the Lost Cabin.

As noted in Figure RJS-9, USEPA monitoring well MW01 is screened in the base of the Lost Cabin Member; whereas, USEPA monitoring well MW02 is screened within the upper portion of the Lysite Member. As will be discussed later, water samples from each well are different especially with respect to sulfate and chloride concentrations. The Lysite is the gas-producing section of the Wind River Formation. Given that the Lysite Member is the primary gas-producing section it is expected to have higher TDS and associated chloride concentrations as chloride concentrations are often elevated in hydrocarbon bearing formations.

The primary sources of the natural gas that is produced from the Wind River and Fort Union Formations in the Pavillion Field are from Cretaceous-aged rocks such as the Cody Shale, which is located stratigraphically below the Wind River and Fort Union Formations (see Figure RJS-6).

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[4] Diagenesis is the process involving physical and chemical changes in sediment after deposition (Bates and Jackson, 1984).

Fluid recoveries from drill-stem tests (to be explained later) demonstrate the presence of gas extending over a vertical distance of more than 10,000 ft (Nelson and Kibler, 2007). The bottom of the gas reservoir lies at the base of the Lower Cretaceous, deeper than shown by drillstem test recoveries. Lacking a continuous barrier to vertical migration, such as the Waltman Shale, the gas extends above what would be the equivalent of the Waltman Shale if it extended to the west (Nelson and Kibler, 2007). Johnson and Rice (1993) noted the lack of significant isotopic variation over large vertical distances based on gas-isotopic data. They concluded that gas (e.g., methane) in shallow formations, such as the Wind River Formation, originated from deep, older strata and migration has occurred for millions of years.

Gas migrates vertically through rock more easily than other fluids such as water due to its physical properties. Shales offer more resistance to the flow of water because water is more viscous (thicker) than gas. Gas will migrate upward away from the reservoir via diffusion[5] caused by concentration gradients. Molecules of gas will tend to migrate from high to low concentrations. Thus, that natural gas is present in the USEPA's groundwater monitoring wells is to be expected, as a result of natural processes that have occurred over millions of years, and are not related to gas development.

Relative to domestic wells, gas was encountered at shallow depths in the Pavillion Field before oil and gas development. In 1951, the US Bureau of Reclamation (USBR) was drilling water-supply wells for its workforce. They found a satisfactory water-bearing unit at a depth of approximately 500 ft bgs, but the water was not potable due to gas (USBR, 1951). The USBR's encountering gas at a shallow depth predates by several years the drilling of the first producing gas wells in the area.

In Figure RJS-9, results of mud logging are provided for gas wells where the log was recorded. The pink coloration shown on the log represents the occurrence of gas. In several instances the mud logs were recorded in the Lost Cabin Member and indications of the presence of gas are

[5] Diffusion is the migration of molecules (e.g., gas) through a fluid or porous medium (e.g., shale or sandstone) in a direction tending to equalize concentrations in all parts of the system (Bates and Jackson, 1984).

noted. As a side note, mud logs are recorded in the open borehole prior to the installation of the production casing, but after setting the surface casing. The indications of gas on the mud log are due to naturally occurring gas. As shown in Figure RJS-9, a gas well that is near USEPA monitoring well MW02 shows the presence of gas at the same depth as well MW02 is screened. If the USEPA had selected other gas production wells in the vicinity of their cross section A-A' they would have found abundant naturally-occurring gas at shallow depth. Figure RJS-10 is another cross section (B-B') that is located in the vicinity of cross section A-A'. As noted in this figure, natural gas was encountered at shallow depths within the Lost Cabin Member. The reason that natural gas is not documented even shallower is that mud gas logging data are not recorded over the surface-casing interval in modern wells. In the construction of a natural gas producing well, the first step is to install a steel surface casing that extends from land surface to depth. As noted in Figure RJS-10, these surface casings are approximately 600 to 800 ft deep. After setting the surface casing, a smaller diameter borehole is subsequently drilled into the Lysite Member of the Wind River Formation, then cased and cemented in order to obtain commercial quantities of gas. Mud logs, in modern wells, start at the bottom of the surface casing and extend to the total depth of the borehole.

Figure RJS-11 is a three-dimensional perspective looking from the southeast towards the northwest; Figure RJS-8 shows the location of this perspective. Figure RJS-11 displays the natural gas "shows" in the vicinity of the two USEPA wells. The locations of these wells are also indicated in the figure. The upper part of the figure is the land surface, so the depth of the view is approximately 1,000 ft bgs. Figure RJS-11 shows graphically that both USEPA monitoring wells were installed and screened in geologic units that contain significant natural gas shows. The difference in coloration in the figure depicts whether or not natural gas is or has been produced from the zone. As noted in the figure, production consistently is from the deeper zones.

The mud log data shown in both cross sections demonstrate that the presence of natural gas in the USEPA monitoring wells should have been expected; mud log data acquired in gas wells drilled five years before the USEPA's wells contained gas where USEPA's wells were screened.

Lastly, deeper domestic wells are more likely to encounter natural gas, as its presence is widespread in the Pavillion Field, and this presence is due to natural processes.

5.0 DISCUSSION OF ANSWERS

Question:

What is the naturally occurring groundwater quality of the water-bearing units of the Wind River Formation?

Answer:

Groundwater quality in the Wind River Basin, the Pavillion Field, and the core area is highly variable due to the anisotropic nature of the geologic units. The sand lenses that are tapped by domestic water wells are discontinuous and the discontinuous nature of the lenses leads to variability in water quality. In the Wind River Formation, the primary constituents that naturally influence the quality of groundwater in the area are sodium, sulfate, and TDS. The TDS of the groundwater from shallow wells in the study area (wells less than 800 ft deep) varies from approximately 200 to over 5,000 mg/L. The secondary drinking-water standard for TDS is 500 mg/L. High TDS water has an objectionable taste. The sulfate concentrations of the water vary from approximately 12 to 3,600 mg/L. The secondary drinking-water standard for sulfate is 250 mg/L. Sulfate in elevated concentrations (above 250 mg/L) in water also has an objectionable taste. Sodium varies from 40 to 1,200 mg/L. There is no drinking-water standard for sodium; however, dissolved minerals, in total, lead to objectionable taste in most waters in the Pavillion Field. Poor groundwater-quality conditions in the Wind River Formation in the Wind River Basin and the Pavillion Field are from the minerals that occur in the geologic materials. The minerals are leached by percolating waters.

Support:

Daddow (1996) found the groundwater quality in the Wind River Formation to be quite variable across the Wind River Basin. The groundwater quality is a function of local recharge, permeability, groundwater flow, and lithologic conditions. Recharge to the groundwater system comes from precipitation on the outcrops of the Wind River Formation, percolation from overlying units such as the Quaternary-aged deposits, as well as infiltration associated with flood irrigation practices. The latter process is a very important component of groundwater

recharge in the Pavillion Field. Flood irrigation involves flooding a field that is used to grow crops, such as hay or alfalfa, with water. This process will occur several times during the growing season. In addition, the irrigation ditches that transport water to the fields are not lined, and thus, water infiltrates to the subsurface and recharges groundwater. The combined effects of flood irrigation and irrigation ditch infiltration leads to the leaching (flushing) of inorganic (e.g., sulfate) as well as organic chemicals (e.g., pesticides, herbicides, and fertilizers) to groundwater as well as enhancing recharge that increases the downward component of groundwater flow that will be discussed later.

The depth to groundwater in the shallow water-bearing zones is on the order of 10 to 15 ft. Morris et al. (1959) found that wells completed in the shallow unconfined water-bearing units show water-level fluctuations mainly due to recharge from irrigation. Fluctuations on the order of 10 ft have been documented for shallow wells (less than 50 ft bgs) (Morris et al., 1959). They also found that irrigation recharges the shallow artesian (confined) water-bearing units as documented in a well located in Section 20 of Township 3 North and Range 2 East, a well close to the core area.

In the Pavillion Field area, water produced from the Wind River Formation is typically highly variable in TDS, sodium, and sulfate concentrations. Sulfate and TDS are typically found in concentrations exceeding USEPA's Secondary Drinking Water Standards[6] (Gores & Associates, 2011).

Gores & Associates evaluated the groundwater quality in their study area by analyzing the distribution of TDS. They found that TDS is primarily made up of sodium and sulfate, thus a groundwater sample with a high TDS concentration will also be high in both sodium and sulfate. The parameter of pH also affects the taste of water and in some instances, natural groundwaters in the Pavillion Field area have measured pHs as high as 10.47 (see Table RJS-1).

[6] Secondary standards are non-enforceable guidelines regulating chemicals that may cause cosmetic effects (such as skin or tooth discoloration) or aesthetic effects (such as taste, color, or odor) in drinking water.

The water quality of domestic wells sampled by the USEPA and Gores & Associates is typically slightly alkaline (just above pH 7), sodium sulfate dominant, and elevated in total dissolved solids. Less commonly, waters that have pHs near 7 (neutral pH conditions), with calcium-sodium bicarbonate dominant type waters are also present. The calcium-bicarbonate water is more similar to the chemistry of surface water in the area, and is a typical groundwater composition for recharge by meteoric water (Freeze and Cherry, 1979).

Concentrations of sodium and sulfate typically increase with TDS and have been attributed to geochemical evolution from interaction with geologic materials, specifically cation exchange of sodium for calcium and leaching of sodium-sulfate salts in the Wind River Formation (Morris et al., 1959). Morris et al. (1959) also presented the water-soluble content of surficial geologic materials in the area, which indicated that the leachate from soil was typically slightly alkaline (pH as high as 10.47) and high in sodium. Groundwater pH in the area increases as sodium replaces calcium as the dominant cation (Figure RJS-12) and is consistent with a geochemical evolution of groundwater chemistry from the near neutral calcium-sodium mixed composition to an alkaline (pH 8.3 to 10.5) sodium-dominant composition. This observation is consistent with other studies of alkaline groundwaters (e.g., Edmunds and Shand, 2008) where the transition from calcium-dominated water to sodium-dominated water occurred as the pH transitioned from near neutral to alkaline (at a pH of approximately 8.3) and is attributed to depletion of the calcite buffering capacity as calcium is removed from solution. As a result, such groundwaters obtain pH values of approximately 8.3 to 10.5, consistent with buffering by CO_3^{2-}, rather than the range more typical of natural waters resulting from buffering by calcite (approximately 5.4 to 8.3). Because of the absence of significant calcite buffering, the alkaline, sodium-dominated groundwaters encountered in the Pavillion Field have a limited buffering capacity when exposed to strong bases such as soda ash and Portland cement chemicals used by the USEPA in the drilling and constructing of their monitoring wells. Additional discussion regarding monitoring-well construction is contained in another section.

Gores & Associates (2011) mapped the groundwater-quality data (TDS) for 70 domestic/municipal wells located in an area that overlaps the current core area (Figure RJS-13).

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As noted in Figure RJS-13, the TDS concentration for the wells can vary from less than 500 to over 1,000 mg/L within a very small area. Gores & Associates also grouped the various wells by depth using three groupings; wells less than 220 ft deep, wells 220 to 600 ft deep, and wells greater than 600 ft deep. The water-quality data were then plotted and analyzed for potential trends. Based on an observation of the plotted data, no notable trend was found. This variability demonstrates that the groundwater quality of wells completed in the Wind River Formation is highly dependent upon the characteristics of the sand lenses that are intersected by the wells.

Table RJS-1 is a tabulation of the water-quality analyses for select constituents performed by the USEPA (2011b). The USEPA did not provide the TDS of their water samples; however, I calculated a value for TDS using a methodology published by Csuros (1997). As noted in Table RJS-1, the TDS varies from 371 to 5,421 mg/L with an average of 1,674 mg/L, a value more than three times the secondary drinking-water standard. The maximum and minimum concentrations are listed, and average concentrations for the other constituents were calculated.

Table RJS-1 shows that the average concentration (991 mg/L) for sulfate is approximately four times the secondary standard. Table RJS-1 lists water analyses for 74 samples and only one sample has a TDS concentration that is less than 500 mg/L, the secondary standard. Table RJS-1 provides the analyses of inorganic constituents for water samples collected from USEPA monitoring wells MW01 and MW02. The data from these two wells show that the waters are different. Water from MW01, a well screened in the Lost Cabin Member is higher in sulfate than MW02 (a well screened in the Lysite Member), but water from MW02 is higher in calcite and chloride than MW01. This distinction indicates that the two geologic members of the Wind River Formation have different water types as discussed above.

Table RJS-2 is a compilation of water-quality data documented by Gores & Associates (2011). Some of the data compiled by Gores & Associates was obtained from the USEPA, but in other cases new data were collected. Again, the maximum, minimum, and average concentrations are

listed, and the conclusion is that the average concentrations of TDS and sulfate would render the groundwater objectionable with respect to taste. Gores & Associates (2011) found that "while the water in many cases is palatably objectionable because of its taste and odor characteristics, it still meets EPA's public water supply standards."[7] In this same report, Gores & Associates goes on to state;

> "Based on the available historical water-quality test results, including qualitative information from area users and well-service providers, groundwater quality in the entire Pavillion area has always been difficult. In summary, this area has never produced high-quality groundwater. With only one or two exceptions..., the private wells meet EPA primary drinking water standards for public water suppliers. However, the water has undesirable taste, aroma, and appearance."

The work by Gores & Associates (2011) contradicts the USEPA's premise that objectionable water was first noticed in 2008. The historical information indicates substantial and previously poor groundwater quality that has always been objectionable.

Question:

What are the horizontal and vertical directions of groundwater flow in the approximately upper 800 ft of the Wind River Formation in the core area shown in Figure RJS-2?

Answer:

The overall horizontal direction of groundwater flow in shallow (approximately top 50 ft of saturated zone) water-bearing zones is towards the southeast in the core area (Figure RJS-2). Groundwater elevation data from existing groundwater monitoring wells, including USEPA's monitoring wells in the core area, indicate that the general vertical direction of groundwater flow is downward from shallow water-bearing zones to deeper groundwater. There is one well completed in the Wind River Formation in the core area that is under artesian, flowing conditions, but this situation is rare. The hydraulic gradient within the gas producing section

[7] Public water-supply standards are the same as the National Primary Drinking Water Standards. These are legally enforceable standards that apply to public water systems. Primary standards protect public health by limiting the levels of chemicals in drinking water.

of the Wind River Formation in the core area and in the Pavillion Field generally follows a normal hydrostatic gradient, contrary to the Draft Report's assertion of an upward flow gradient or an unknown flow gradient. A downward hydraulic gradient means that chemicals at depth cannot migrate upward. Pressure transients induced by hydraulic fracturing are of such short duration that chemical transport is governed more by the long-term hydraulic gradients that are downward.

Support:

The USEPA (2011b) states that hydraulic gradients are undefined in the area of investigation, but that there are flowing stock wells in the same area. The USEPA cites one well, PGDW44, that is flowing. By inference, the Draft Report suggests that there are many flowing wells in the Pavillion Field, and uses this concept to conclude that there is an upward hydraulic gradient away from the gas production wells towards the shallow domestic wells in the Pavillion Field. This is not the case. There is clearly a downward component of groundwater flow in the vicinity of both of USEPA's wells, and that the horizontal flow direction of shallow groundwater (unconfined) is towards the southeast.

Prior to providing additional discussion on hydraulic gradients, I want to provide a brief description on groundwater flow. Figure RJS-14 is a cross section of a conceptual hydrogeologic model for groundwater flow in the study area. This conceptual model shows the Wind River and Fort Union Formations cropping out on the flanks of the mountains and thickening eastward (the wedge of rock discussed earlier). The lenses of sandstones and shales within the formations dip in an easterly direction towards the center of the basin.

A basic principal of hydrogeology is that groundwater flows from higher total potential to lower total potential. Potential is a measure of how much energy is in the groundwater and potential energy for groundwater is measured through the use of wells. The water level in a well, when referenced to mean sea level, is a measure of how much energy the groundwater has in terms of feet above mean sea level. Groundwater will move to a location where it has lower total potential (lower elevation measured in a well). Groundwater loses energy as it moves through

the rock or soil due to friction. It must be emphasized that groundwater flows at very low velocities; generally groundwater flows on the order of a few feet to a few hundred feet per year based upon the hydraulic conductivity[8] of the geologic materials, the hydraulic gradient (the difference in total potential between two points divided by the distance between the two points), and porosity.

Encana has installed groundwater monitoring wells as part of site investigation and monitoring activities at three Wyoming Voluntary Remediation Program (VRP) sites. These sites are discussed in another section. Given the size and areas of these sites, relative to the size of the Pavillion Field, I averaged the groundwater elevations measured in the wells located in the vicinity of each of the former pits in order to estimate the total potential of groundwater at each location. These groundwater elevations are referenced to feet above mean sea level (ft amsl), the survey datum. The water levels in the VRP monitoring wells were measured in April 2010. The USEPA provided depths to groundwater in their two monitoring wells for April 2011; however, they do not provide ground-surface elevations for the monitoring wells. This type of information is expected in a standard hydrogeology report. The elevations of the USEPA wells were estimated from a USGS topographic map that has a contour interval of 20 ft, thus the estimated elevation is ±10 ft of the actual elevation. Figure RJS-15 of this report shows the locations of the three VRP sites and the USEPA monitoring wells. As noted in the figure, the three VRP sites form a triangle around USEPA monitoring well MW01. The horizontal groundwater flow direction calculated using water-level data from the three VRP sites is towards the southeast at a horizontal hydraulic gradient of approximately 0.006 ft/ft, a low hydraulic gradient.

[8] An important parameter in the field of hydrogeology is hydraulic conductivity. This parameter is used to calculate how much and how fast (velocity) groundwater moves. Hydraulic conductivity is a measure of the ability of a geologic material to transmit water. For example, a sand or gravel unit has a relatively high hydraulic conductivity because it can easily transmit water; clay does not transmit water readily, and thus, would have a low hydraulic conductivity. Hydraulic conductivity is similar to permeability but in the case of hydraulic conductivity the wetting fluid is water at a standard temperature and density.

Using the groundwater flow direction and the calculated hydraulic gradient, the water table (the top of the saturated zone where groundwater is at atmospheric pressure) is estimated to be at an elevation of approximately 5,359 ft amsl in the area of USEPA MW01. The estimated groundwater elevation in USEPA MW01 is 5,167 ft amsl. Given that the groundwater elevation in the monitoring well is lower than the elevation of the water table, the vertical groundwater flow direction is downward at a vertical hydraulic gradient of approximately 0.25 ft/ft. Potential variations in water-level elevations (even a difference of 10 ft) for the USEPA monitoring well, due to the lack of survey information from the USEPA, do not alter the fact that the vertical hydraulic gradient is downward.

As previously discussed, the USEPA has suggested that there is an upward hydraulic gradient in the Pavillion Field area based on one flowing artesian stock well (PGDW44) in the core area shown in Figure RJS-15. A review of McGreevy et al. (1969) shows that, of the approximately 174 wells that are completed in the Wind River Formation in the area that McGreevy et al. studied, 13 wells are flowing and these are located across their study area. McGreevy et al.'s study area was 3,500 square miles in size. It appears that the one well referenced by the USEPA is the only flowing well in the core area shown in Figure RJS-15. There are approximately 44 groundwater wells (excluding monitoring wells at VRP sites and the USEPA monitoring wells) in the core area. Given the isolated nature of the sand lenses within the Wind River Formation, the presence of one well in an eight-square mile area should not be the basis for stating that there is an upward groundwater flow direction throughout the area of the Pavillion Field. In fact, measured groundwater elevations in shallower wells surrounding, or in the vicinity of, USEPA's own wells demonstrate the opposite.

Figure RJS-15 also shows the locations of domestic wells in the study area. Pertinent information regarding each well is also provided, if available. This information includes well depth and depth to groundwater. Groundwater elevations are also posted, and many of these elevations are from historical records. Given that the area is not experiencing large groundwater withdrawals, significant differences in groundwater elevations (e.g., tens of feet) over time are not expected. A review of Figure RJS-15 indicates that groundwater elevations are

variable most likely due to the discontinuous nature of the sandstone lenses; as such, variable groundwater elevations (total potentials) are expected. In reviewing the water levels in wells that are in close geographic proximity to the areas of MW01 and MW02 but at different depths, the overall observation is that there is a downward gradient. The information used to construct Figure RJS-15 is provided in Table RJS-3.

The hydraulic gradient within the gas producing section of the Wind River Formation (Lysite Member) generally follows a normal hydrostatic gradient, meaning that the section is normally pressured. A normal hydrostatic gradient (for water) is approximately 0.433 pounds per square inch (psi) per foot of depth (~0.433 psi/ft). Bjorklund (1978) reported the pressure gradient within the Pavillion Field to be approximately 0.421 psi/ft or slightly less than hydrostatic. Nelson and Kibler (2007) also observed a normal pressure gradient within the Pavillion Field and graphed what are termed "shut-in" pressure[9] data to show a 0.433 psi/ft gradient extending to a depth of approximately 12,000 ft in the Cody Shale. Figure RJS-16 shows the shut-in pressures for different geologic units with depth along with various pressure gradients. As noted in this figure, most pressure measurements are plotted on or below the hydrostatic gradient line. Most elevated pressures (above the gradient line) are associated with deeper formations.

Drillstem tests (DST)[10] in the Pavillion Field do not indicate reservoir pressures greater than hydrostatic. In fact, many DSTs performed post-1990s reflect the influence of infilling development (installation of closer-spaced gas production wells) and indicate the depletion of reservoir pressures within the Wind River Formation. Figure RJS-17 shows the original reservoir pressure gradient of 0.421 psi/ft calculated by Bjorklund (1978) along with measured formation pressures. Since the field's discovery in the 1960s no pressure gradients have been recorded

[9] Shut-in pressure is the surface force per unit area (e.g., psi) exerted at the top of a wellbore when it is closed at the top of the well.
[10] A DST is a well test conducted with the drillstring still in the hole. DSTs are typically performed on exploration wells, and are used to assess whether there is a commercial reservoir to produce hydrocarbons. The most common test sequence consists of a short-flow period followed by a pressure-buildup period that is used to estimate initial reservoir pressure. Other actions are performed to assess other properties of the potential reservoir unit.

above hydrostatic. As noted in the figure, many pressures were below a gradient of 0.150 psi/ft, indicating pressure depletion.

The information provided in Figures RJS-16 and RJS-17 contradicts the USEPA's assertions that the Pavillion Field is over pressured and that there is an upward gradient. The field data indicate the opposite.

Question:

Will groundwater pumping from individual domestic wells impact groundwater flow directions in the Pavillion Field area?

Answer:

Pumping from an individual domestic well in the core area does not have a significant impact on groundwater flow directions, and the radius of the zone of capture exerted by a well is likely less than 100 ft. This limited zone of capture is primarily due to the low pumping rates (average of less than 1 gpm) from individual wells.

Support:

McGreevy et al. (1969) provide groundwater pumping rates and measured drawdown for three wells that are located within or near the focused study area and that are completed in the Wind River Formation. From these data, specific capacities (pumping rate/drawdown) for the wells were calculated. A transmissivity (hydraulic conductivity multiplied by thickness of water-bearing unit) of the water-bearing zone can then be estimated from the specific capacities as outlined in McGreevy et al. (1969). The calculated mean hydraulic conductivity of the geologic materials is 0.5 ft/d.

The average pumping rate for an individual domestic well was calculated to be 480 gallons per day based upon an average domestic usage of 160 gallons per day per person. Each residence is assumed to have three persons and this assumption is consistent with Gores & Associates (2011). In order to be on the conservative side (over-estimating impacts), I assumed an average

daily per person consumption of 160 gallons. Gores & Associates (2011) assumed 80 gallons per person per day for the Town of Pavillion; however, Pavillion prohibits the use of treated municipal water for irrigation. I have allocated an additional 80 gallons per day per person for irrigation of landscaping around the house. In the non-growing months (about seven to eight months) of the year, irrigation would not occur.

McWhorter and Sunada (1977) provide a methodology to calculate the radius of the zone of capture by a pumping well located in a uniform, isotropic, homogeneous extensive water-bearing zone. For my analysis, I used a hydraulic conductivity of 0.5 ft/d, a thickness of 94 ft and a hydraulic gradient of 0.006 ft/ft. An assumption in this analysis is that there are no other pumping wells close to the well of interest (e.g., more than several hundred feet). Assuming a pumping rate of 480 gallons per day, I calculate that a well would have a radius of influence of about 100 ft. Given the isolated nature of the water-bearing zones, more limited (smaller radius) and isolated influences than calculated would be observed.

Question:

Are any public drinking water wells threatened?

Answer:

The core area that comprises the eight sections shown in Figure RJS-2 does not contain any public drinking water wells. Individual households use wells for domestic use or stock watering. The municipal wells for the Town of Pavillion are upgradient of the core area (a distance of approximately 1.5 miles) and are not impacted by Pavillion Field-related water-quality concerns.

Support:

There are approximately 44 wells located throughout the eight square miles of the area (core area) shown in Figure RJS-2. Of these 44 wells, 27 have permits from the Wyoming State Engineer. The use of the water is classified on the permits. In the eight sections, four wells are

for monitoring, five are classified as strictly domestic, six as stock, 11 are classified as domestic/stock, and one is industrial. None of the wells are classified for municipal use.

The Town of Pavillion is to the west of the Pavillion Field. The wells are hydraulically upgradient of the core area shown in Figure RJS-2, meaning that groundwater in the Pavillion Field flows away from the municipal wells. Thus, the municipal wells are not threatened by water quality in the Pavillion Field.

Question:

Are the former production pit areas potential sources of "groundwater contamination" that result in what the USEPA describes as "plumes of unknown extent?"

Answer:

Encana has studied 33 former production pits in the Pavillion Field area. Encana identified four historical pit areas associated with impacted groundwater, and Encana is working with the WDEQ to address these pits. As part of their investigations, Encana has assessed the extents of groundwater impacts at three of the four sites. At three of the sites, the investigative work to date confirms that no domestic wells have been impacted; at the fourth site, preliminary field work to assess extents has been initiated; however, based upon information from the three other sites, the extent of groundwater impacts is also expected to be limited, with no impact to any domestic wells. In summary, former pits are not a significant source or threat to groundwater quality in the Pavillion Field.

Support:

The USEPA states in their Draft Report that chemicals in groundwater

> "...near pits indicates that pits are a source of shallow ground water contamination in the area of investigation. When considered separately, pits represent potential source terms for localized ground water plumes of unknown extent. When considered as a whole they represent potential broader contamination of shallow ground water. A number of stock and domestic wells in

the area of investigation are fairly shallow (e.g., <30 meters below ground surface [less than 100 feet]) representing potential receptor pathways."

The USEPA's sweeping statements give the reader the impression that all of the historical production pits in the Pavillion Field are sources of groundwater contamination, and that this contamination is widespread and threatens the quality of water in domestic wells. The USEPA's representation conflicts with the facts.

Starting in 2005, Encana has voluntarily evaluated a total of 33 former historical pit locations and found impacted groundwater quality at four locations. The remaining 29 locations were determined to have not impacted groundwater.

Encana has entered the four sites into the Wyoming Voluntary Remediation Program (VRP), administered by the WDEQ. Encana collected and analyzed water samples from nearby landowners' wells at the request of WDEQ to ensure there was no impact. The results of this analysis indicated no impact to groundwater quality in the owners' wells.

The four VRP sites are shown in Figure RJS-15. Figures RJS-18, RJS-19, and RJS-20 are maps of three individual VRP sites. These figures document the locations of Encana groundwater monitoring wells, the direction of groundwater flow (generally towards the southeast), and distances to the nearest domestic wells. In addition, the estimated extent of benzene in groundwater at each location is displayed. Benzene is the chemical of primary concern at sites such as former production pits that involve petroleum hydrocarbons. Also shown in the figures are tables of analytical data for groundwater samples collected from the Encana monitoring wells. A review of the groundwater data and the inferred extents of benzene demonstrate that the areas where benzene has impacted groundwater quality are limited and no domestic wells have been impacted. The fourth site (Blankenship Fee 4-8 in Figure RJS-15) has had an initial investigation. At this time the amount of field investigation is not as extensive as at the other three; however, an additional site investigation plan is forthcoming. An initial groundwater concentration for benzene at the fourth site is approximately 100 µg/L (parts per billion); a

concentration less than two of the other three sites. Based upon this relatively low concentration the extent of benzene in groundwater is expected to be less than a few hundred feet downgradient of the former pit. The nearest domestic well from the fourth site is approximately 1,500 ft downgradient of the former pit.

The data gathered by Encana refute the USEPA's statement that the groundwater impacts from the pits are "plumes of unknown extent." In addition, the investigations conducted and data collected by Encana counter the notion that there is "broader contamination of shallow ground water." In summary, the pit-related impacts to groundwater quality are generally known; they are localized and limited in area. Lastly, domestic wells are not impacted.

Question:

Did the USEPA and their contractors properly install, complete, and develop their two groundwater monitoring wells so that groundwater samples collected from them accurately represent ambient conditions of the water-bearing zones?

Answer:

The USEPA did not properly install, complete, and develop their two groundwater monitoring wells. As such, the analyses of water samples collected from both monitoring wells do not accurately represent ambient conditions of the water-bearing zones and cannot support decision making.

Support:

The USEPA does not provide complete documentation on how the wells were installed, completed, or developed. The information that was supplied is inconsistent in several instances as will be described in this section. The USEPA provided daily activity reports that describe what occurred on a particular day. The daily activity logs are handwritten (in some cases the writing is difficult to decipher). In addition, Shaw Engineering, the USEPA contractor that supervised the installation and development of the wells, also labeled each of the two wells as MW01, but distinguished the wells based upon the ownership of the land. In reviewing the handwritten

activity logs, it is sometimes difficult to ascertain which well is being referenced for a particular activity. In their Draft Report (2011b), the USEPA does not discuss the rationale for their well design, e.g., screen slot size, length of screen, and materials used. Also, the well completion diagrams provided in the field notes (cuttings descriptions) are different than those provided in the Draft Report. For example, the field notes show the casing for one of the wells as being black steel and what appears to be "steel TNC casing" for the other; whereas, in their Draft Report, the USEPA shows them as stainless steel. A review of the literature does not yield a definition for TNC steel casing. As previously mentioned, the handwritten notes are difficult to decipher. A more plausible explanation is that TNC is really T&C which stands for "thread and coupling." Thus, the casing used was steel with thread and coupling. There is no indication that the casing is stainless steel. This difference in material can influence water quality, but more importantly this discrepancy is not explained. The difference between stainless steel and black steel are readily apparent in the field. As such, I put more confidence in the field geologists' notations rather than in the USEPA's Draft Report. Also, the well completion diagram (Figure 6a in USEPA, 2011b) shows Portland cement between casing and borehole wall from 0 to 960 ft bgs. This is clearly an error as the well is 785 ft deep.

The wellbore diagrams presented by the USEPA in April 2011 (USEPA, 2011a) document the backfill of the USEPA monitoring wells below the screens with drilling mud and drill cuttings. These diagrams and the document in which they were presented were dated nine months after these wells were installed and they are written in the future tense, which is odd, given that they were written after the fact. The diagrams were subsequently changed for the Draft Report (USEPA, 2011b) to indicate that MW01 was backfilled with cement grout. The diagram for MW02 still shows cuttings in the bottom of the well. Leaving cuttings in a borehole, especially cuttings that contain drilling fluids, is unacceptable in the hydrogeology profession for completing a groundwater monitoring well that is used to assess groundwater quality. The presence of cuttings in a wellbore can influence the water quality in the well because as the well is pumped, water from beneath the screen will migrate towards the well due to the lower total hydraulic potential in the well. Water migrating through the cuttings can leach chemicals

contained in the cuttings and transport chemicals to the well influencing the water quality. The cuttings/drilling fluids contain soda ash (a caustic chemical), as well as other chemicals.

Well development is an important step in having an efficient well capable of providing reliable water samples. Well development includes procedures that are designed to maximize well specific capacity (flow/drawdown). It has two broad objectives: 1) to repair aquifer damage near the borehole that was caused by the drilling operations, so that natural hydraulic properties are restored; and 2) to alter the basic physical characteristics of the water-bearing unit near the borehole so that water flows more freely to a well. These objectives are accomplished by applying some form of energy to the well and water-bearing zone.

The Wyoming Oil and Gas Conservation Commission (WOGCC) reviewed the USEPA daily activity logs and had extensive comments regarding them, especially with respect to well development. In reviewing the WOGCC comments, I determined that they are comprehensive and cover aspects that are important. As such, my opinions regarding development coincide with their analysis. The primary points that WOGCC made were:

- The development of monitoring well MW02 was very difficult.
- Well development of MW02 was sufficient to allow methane to enter the well, but not sufficient to open the screen to allow significant flows of water to enter. (As noted earlier in this report, MW02 was screened in the gas producing Lysite Member.)
- Several thousand gallons of water were removed from well MW01 during development, but only a few hundred gallons appear to have been removed from MW02.
- There does not appear to be sufficient documentation on how much water and mud were lost to the formation during drilling of either well.
- Turbidity[11] data for well MW02 indicate that the well was not developed sufficiently to meet the initial criterion set by the USEPA of less than 10 nephelometric turbidity units (NTU) to consider development complete. The last turbidity readings prior to sampling in October 2010 were made on September 10, 2010. The final reading on

[11] Turbidity refers to solids and organic matter that do not settle out of water. Turbid water samples can affect their chemical analyses.

> this date was 82.1 NTU. There is no explanation by the USEPA as to why and how the NTU readings dropped when sampling occurred. The turbidity values when water samples were collected from MW02 did not achieve the criteria of 10 NTU. The values were 28.8 NTUs for the 2010 sampling and 24 NTUs for the 2011 sampling. The USEPA does not provide a discussion of why they could not achieve the criteria during sampling.

The issue of high pH in the groundwater samples from MW01 and MW02 was addressed by the USEPA through geochemical modeling. The USEPA used modeling because they rejected the potential that the high pH resulted from cement-grout invasion into the screened sections of the wells or other problems with well construction or development. USEPA should have more carefully evaluated cement grout or other well completion causes for the high pH.

Portland cement is a common construction material used in a variety of applications, including well construction. Nielson (2006) offers the following guidance regarding the use of cement in monitoring well construction.

> "Depending on the chemical formulation of the cement, the fineness of the grind, and the conditions under which the slurry is placed, there is an optimum range for the amount of mix water that will completely react or combine with the cement. For normal ASTM Type I Portland cement mixtures, 5 to 6 gal of water is recommended. Excess water that does not combine chemically with the cement, referred to as "bleed water," is very highly alkaline. This bleed water can separate from the slurry, percolate through or along the cement seal surrounding the casing, and infiltrate through or bypass the bentonite chip or pellet seal surrounding the casing, and infiltrate through or bypass the bentonite chip or pellet seal and secondary filter-pack sand, to contaminate water collected as a sample from the well (Evans and Ellingson, 1988). Bleed water can be minimized or eliminated by strictly controlling the amount of mix water used during cement preparation, and measuring the cement slurry density with a mud balance.
>
> ...Proper mix-water ratios should be adhered to as part of a documentable quality control program. Preferably, a mud balance, Marsh funnel, or some type of viscosity meter should be used to determine if proper ratios have been achieved. A slurry with too much water may create a permanent water-quality problem which may lead to the need to decommission the monitoring well (Williams and Evans, 1987).

...Neat cement, because of its chemical nature...is a highly alkaline substance (pH from 10 to 13), and thus introduces the potential for significantly raising the pH of the water with which it comes in contact. Raising the pH, in turn, can affect other chemical constituents in the water (e.g., causing dissolved metals to precipitate from solution). In addition, because the mixture is a slurry and because it is generally placed in a column which imparts a high hydraulic pressure, it may tend to infiltrate into the coarse materials that comprise either the secondary or primary filter pack. This is particularly true of thinner slurries (i.e., those mixed with more than 6 gal of water per sack of cement). The cement infiltration problem can be aggravated in this situation if well development is attempted before the cement has completely set.

All of these issues can result in severe and persistent effects on both the performance of the monitoring well (in terms of yield) and the quality of samples taken from the monitoring well. Placement of a thin grout directly on top of the primary filter pack, with subsequent infiltration, will result in the plugging of the filter pack (and potentially the well screen) with cementitious material upon setting. Additionally, the presence of high pH cement within or adjacent to the filter pack will cause anomalous pH readings in subsequent water samples collected from the well. Dunbar et al. (1985) reported an incident attributed to this phenomenon, in which several wells completed in this manner in low-permeability geologic materials consistently produced samples with a pH greater than 9 for 2.5 yr, despite repeated attempts at well development. Neat cement should never be placed directly on top of the primary filter pack in a monitoring well. It has been suggested in this chapter and by others that a very fine-grained secondary filter pack from 2 to 3 ft thick, be placed atop the primary filter-pack material before placement of the neat cement grout, to minimize or eliminate the grout infiltration potential (Ramsey and Maddox, 1982; Barcelona et al., 1985a)."

As discussed above by Nielson (2006), well completion problems associated with cement can cause high pH and other problems with the quality of samples collected from the well. Figures RJS-21 and RJS-22 illustrate the relationship between pH and calcium, and pH and potassium in the domestic and the USEPA monitoring wells located in the Pavillion Field area, and in the pore water of Portland cement. Pore-water composition for Portland cement is from Alonso et al. (2007) and should be similar for bleed water, which is pore water that is expunged during setting of the cement. As previously presented, Figure RJS-12 illustrates that the relationship between decreasing Ca/Na ratios and increasing pH that is apparent in domestic wells is not

consistent with that of the USEPA monitoring wells. The USEPA monitoring wells have higher pH (11.2 to 12.0) that is indicative of a strong base (e.g., KOH), rather than CO_3^{2-} in the absence of Ca, and their Ca/Na ratios are elevated relative to the groundwater trend apparent in all other samples from domestic wells. The relationship, however, between Ca/Na ratios and pH in the USEPA monitoring wells is consistent with mixing of Portland cement pore water (or bleed water) with mildly alkaline, sodium-dominant groundwater, such as that observed in domestic wells in the Pavillion Field. The relationship between pH and calcium concentrations is illustrated in Figure RJS-21, and also indicates that the composition of water samples from the USEPA monitoring wells is consistent with mixing of Portland cement pore water (or bleed water) with mildly alkaline, sodium-dominant groundwater as the USEPA's wells' chemistry is between the cluster of domestic wells and Portland cement pore water. It is also noteworthy that the composition of samples from the USEPA monitoring wells is inconsistent with any of the other wells in the area. Similarly, the relationship between potassium concentrations and pH (Figure RJS-22) illustrates that the potassium concentrations from the USEPA monitoring wells are notably higher than those observed in any of the other wells in the area, but are in line with mixing of Portland cement pore water (or bleed water) with mildly alkaline, sodium-dominant groundwater.

The water quality observed in the USEPA monitoring wells is typical of that for monitoring wells with completion problems associated with cement, such as in cases where too much water was used in the cement mix, well completion was attempted before the cement had set completely, or secondary filter packs were insufficient or not used. The chemistry from these wells:

1) is consistent with mixing of groundwater and pore water (or bleed water) from Portland cement,
2) has a highly alkaline pH that is outside of the buffering range observed for all of the other wells in the area,
3) has potassium concentrations that exceed those from any of the other wells in the area, and
4) has inconsistent relationships
    a) between Ca/Na ratios and pH, and

b) between calcium concentrations and pH than any of the other wells in the area.

Furthermore, there is no indication that the factors affecting the water quality in the USEPA monitoring wells have affected any of the other wells in the study area.

The USEPA states that the high pHs remained despite their supposed rigorous well development. In reviewing pH data published by the USGS, as well as pH data provided in the USEPA's Draft Report, no other water sample from any domestic or municipal wells in USEPA's study area or in McGreevy et al.'s study area have pH values as high as those measured in the USEPA wells. The overwhelming field data demonstrate that the high pH waters from the monitoring wells are unique only to these two wells. The data indicate that the wells have been compromised either due to well construction techniques or poor development practices or both. As such, analyses of water samples from either well are not suitable for decision making purposes or for drawing conclusions regarding sources of chemicals in groundwater.

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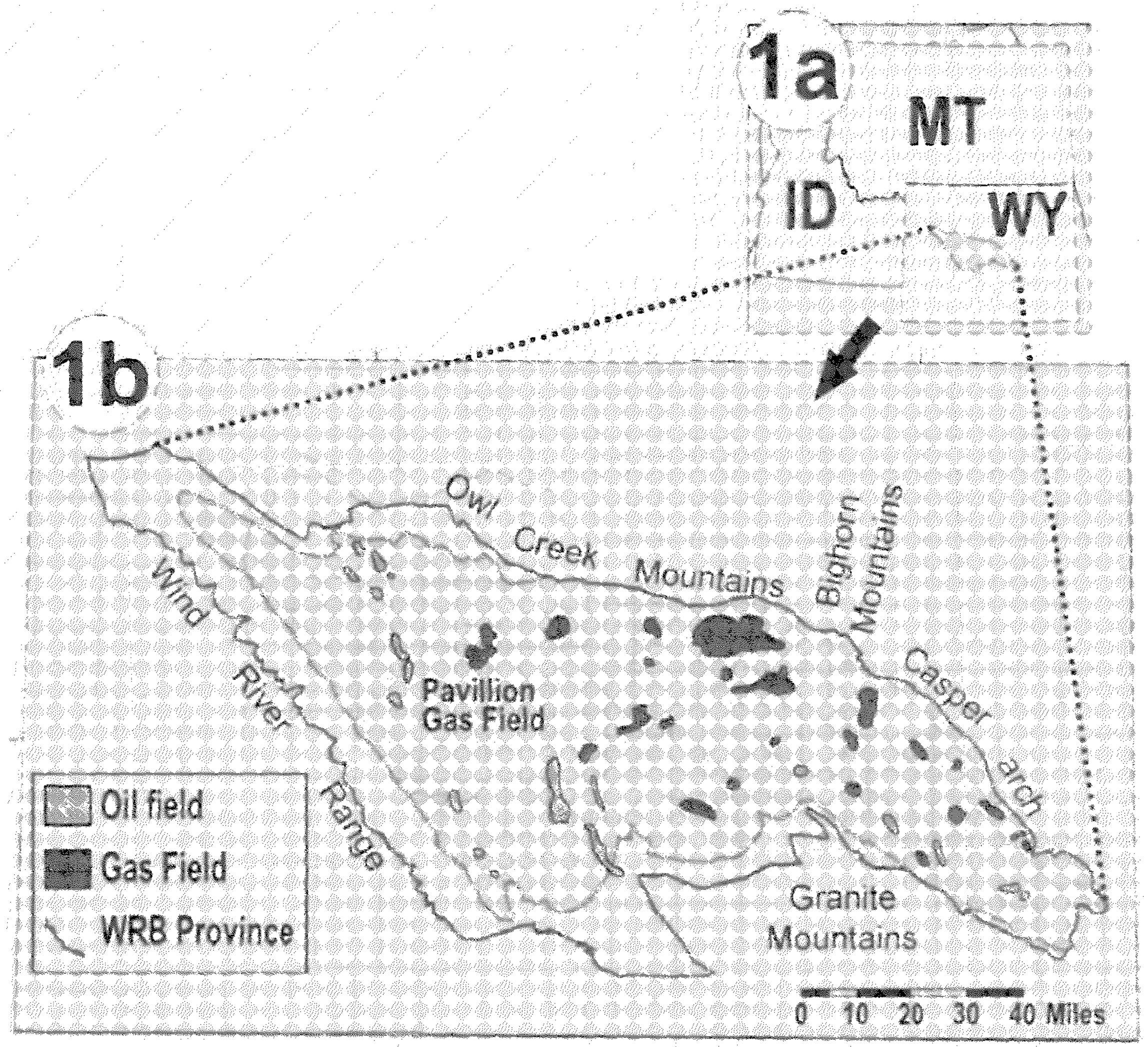

Source: USEPA, 2011

PROJECT NO.	1972
BY	OTHERS
CHECKED	RJS
DRAWN	OTHERS/SAC
DRAWING NAME	SITE–MAP
DRAWING DATE	7 MAR 2012
REVISION DATE	--

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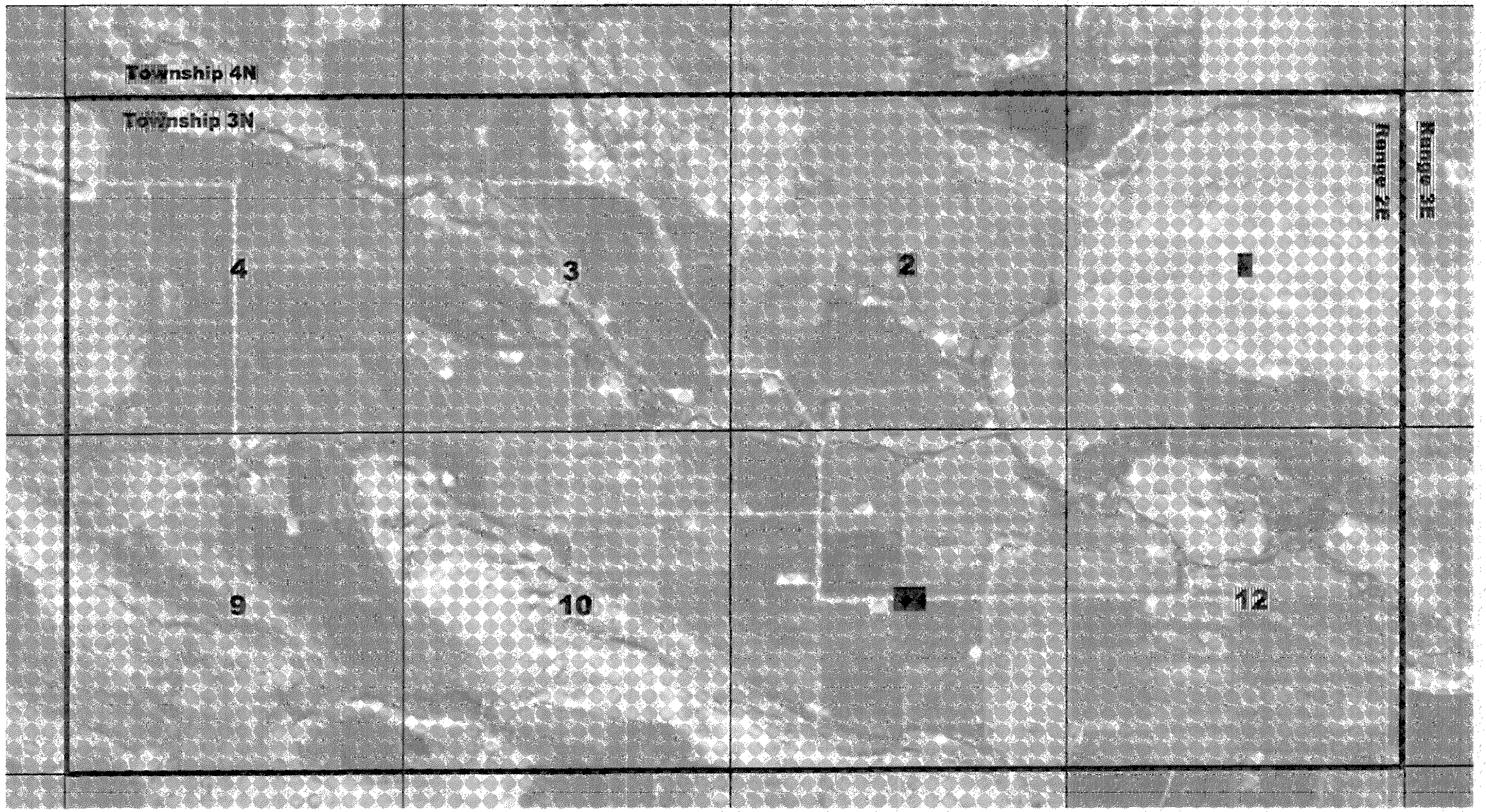
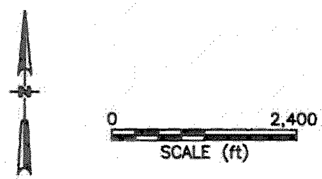
Denver, Inc.

Locations of Wind River Basin and Pavillion Field

CLIENT: Encana

FIGURE NO. RJS-1





PROJECT NO.	1972
BY	OTHERS
CHECKED	RJS
DRAWN	OTHERS/SAC
DRAWING NAME	LOC-MAP
DRAWING DATE	7 MAR 2012
REVISION DATE	--

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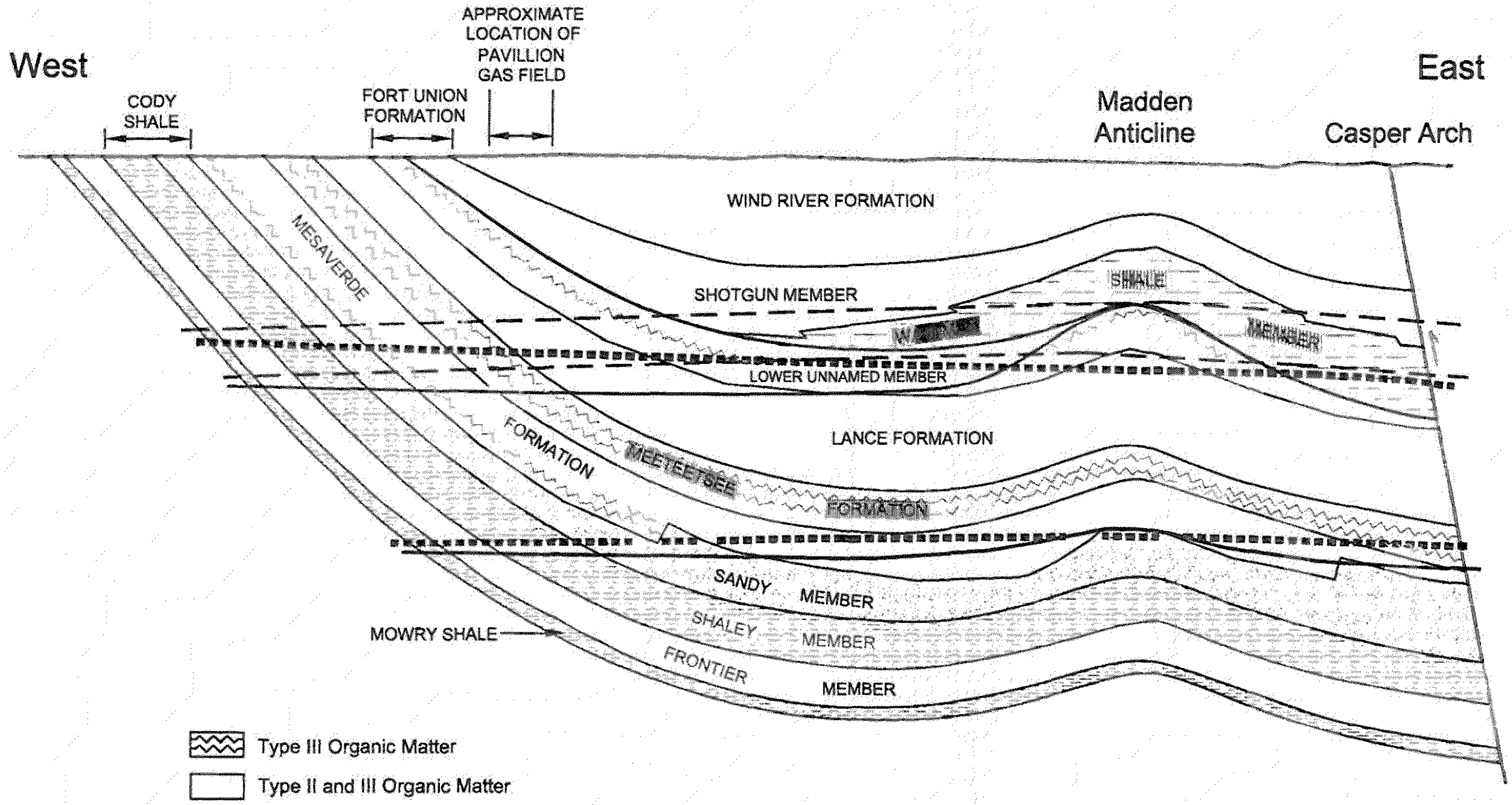
Map of Core Area

CLIENT: Encana

FIGURE NO. RJS-2



Adapted from Johnson et al., 1995

PROJECT NO.	1972
BY	OTHERS
CHECKED	RJS
DRAWN	OTHERS/SAC
DRAWING NAME	SCHEM–E–W–XSEC
DRAWING DATE	7 MAR 2012
REVISION DATE	––

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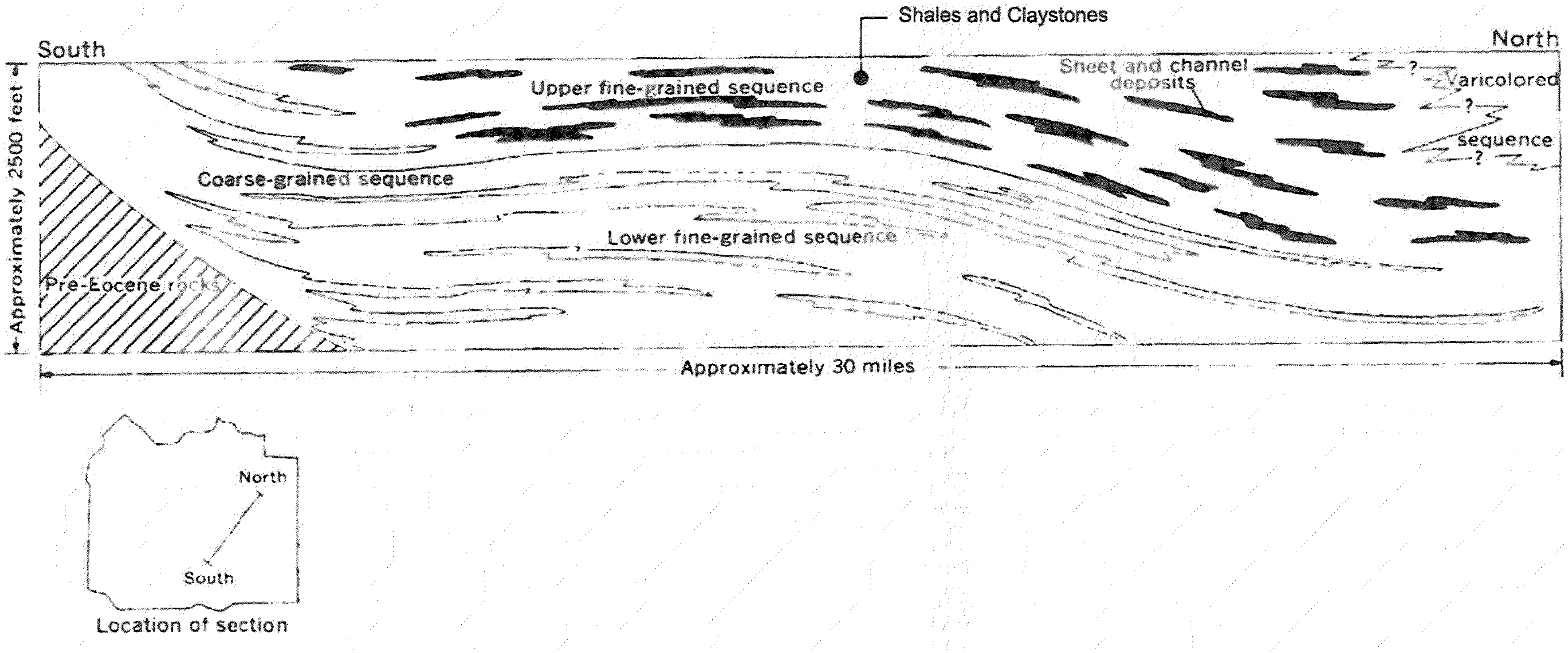
Generalized West-East Cross Section Showing Waltman Shale

CLIENT: Encana

FIGURE NO. RJS-3



Source: McGreevy et al., 1969

PROJECT NO.	1972
BY	OTHERS
CHECKED	RJS
DRAWN	OTHERS/SAC
DRAWING NAME	GEN-XSEC
DRAWING DATE	7 MAR 2012
REVISION DATE	--

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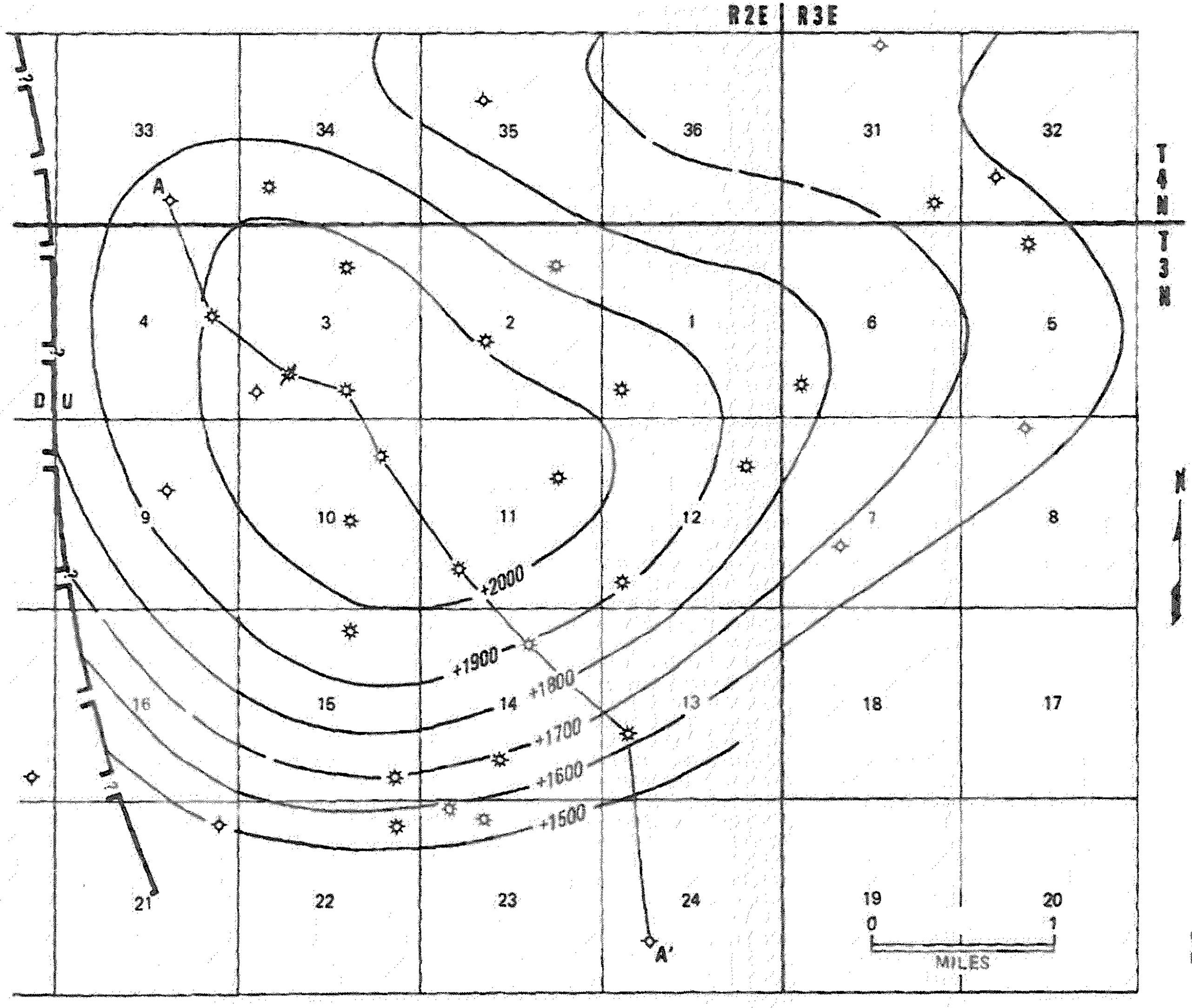
Generalized Cross Section Showing Various Sequences Within the Wind River Formation

CLIENT: Encana

FIGURE NO. RJS-4



Contours in ft. above mean sea level

Source: Bjorklund, 1978

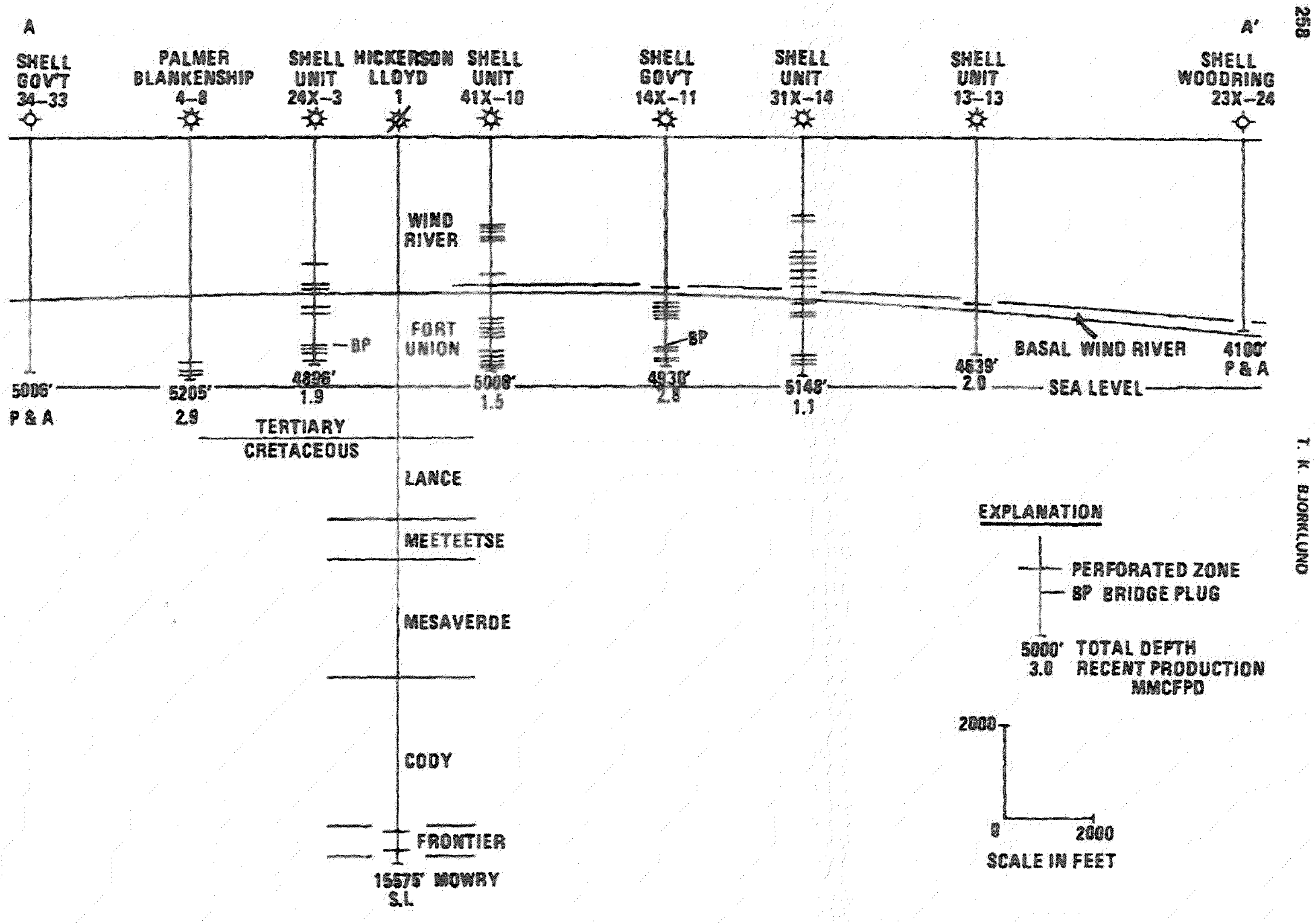
PROJECT NO.	1972
BY	OTHERS
CHECKED	RJS
DRAWN	OTHERS/SAC
DRAWING NAME	STRUCTURAL-CONT-MAP
DRAWING DATE	7 MAR 2012
REVISION DATE	--

ITASCA™ Denver, Inc.

Structural Contour Map of Pavillion Field, Contours of Top of Fort Union Formation

CLIENT: Encana

FIGURE NO. RJS-5



See Figure 6 for Location of Cross Section

Source: Bjorklund, 1978

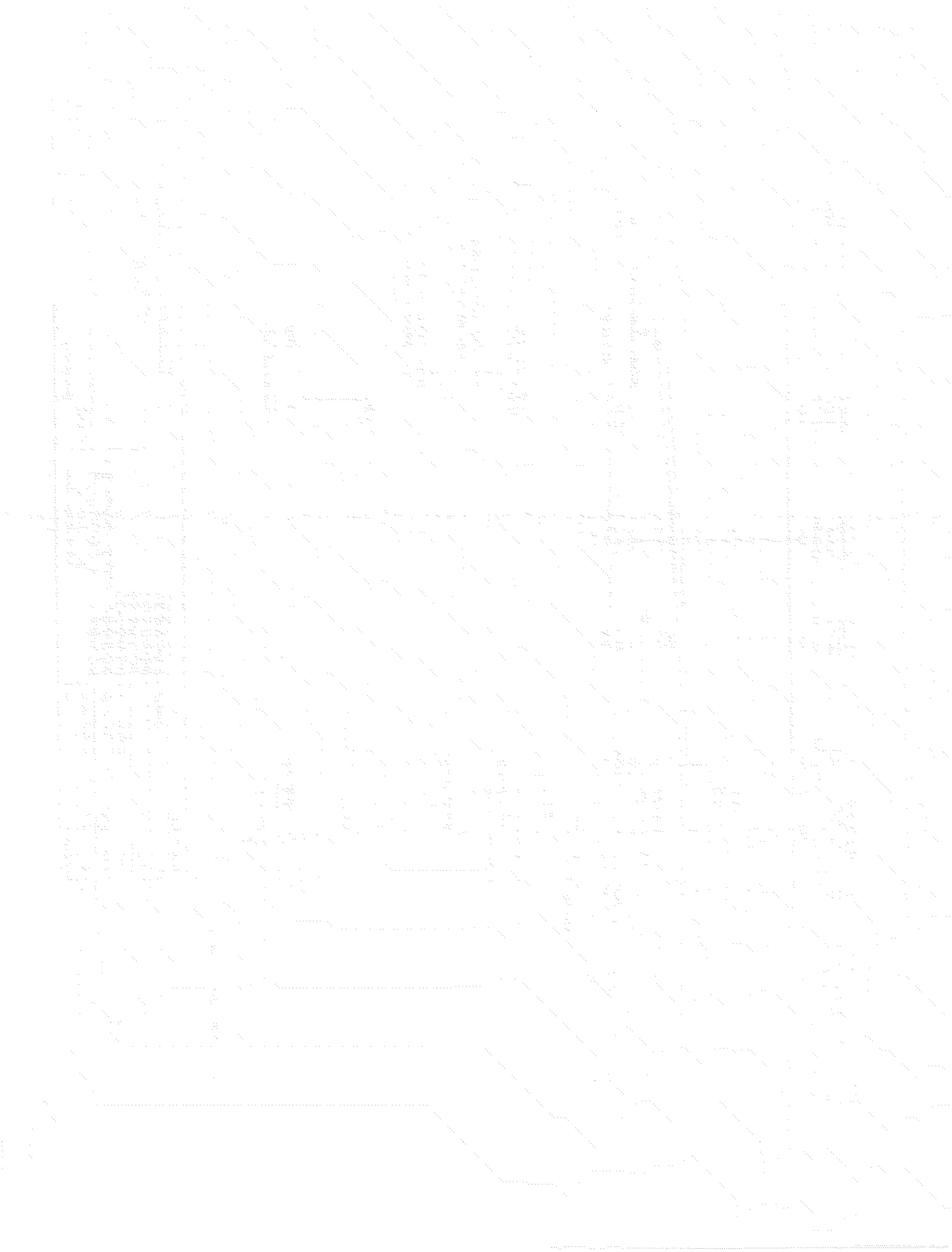
PROJECT NO.	1972
BY	OTHERS
CHECKED	RJS
DRAWN	OTHERS/SAC
DRAWING NAME	XSEC–AA
DRAWING DATE	7 MAR 2012
REVISION DATE	--

ITASCA™ Denver, Inc.

Bjorklund's Cross Section A-A' of Pavillion Field

CLIENT: Encana

FIGURE NO. RJS-6



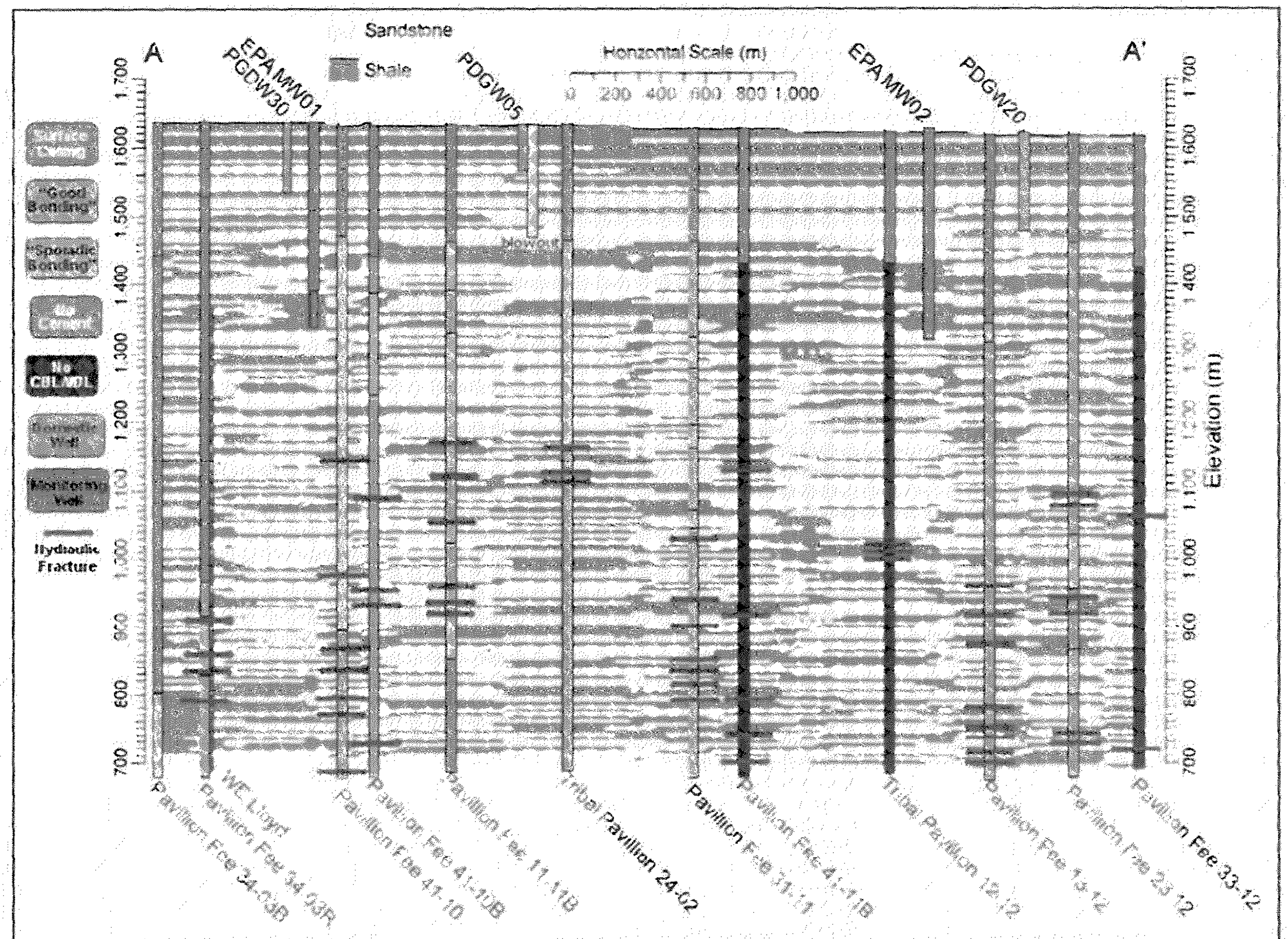


Figure 20. Lithologic cross-section along transect illustrating production wells (with evaluation of CBL/VDLs), domestic wells, and blowout location. Red arrows denote depths of hydraulic fracturing of unknown areal extent. Sandstone units are undifferentiated between fine, medium and coarse-grained units.

Source:USEPA, 2011b

PROJECT NO.	1972
BY	OTHERS/RJS
CHECKED	RJS
DRAWN	OTHERS/SAC
DRAWING NAME	EPA–FIG20
DRAWING DATE	7 MAR 2012
REVISION DATE	--

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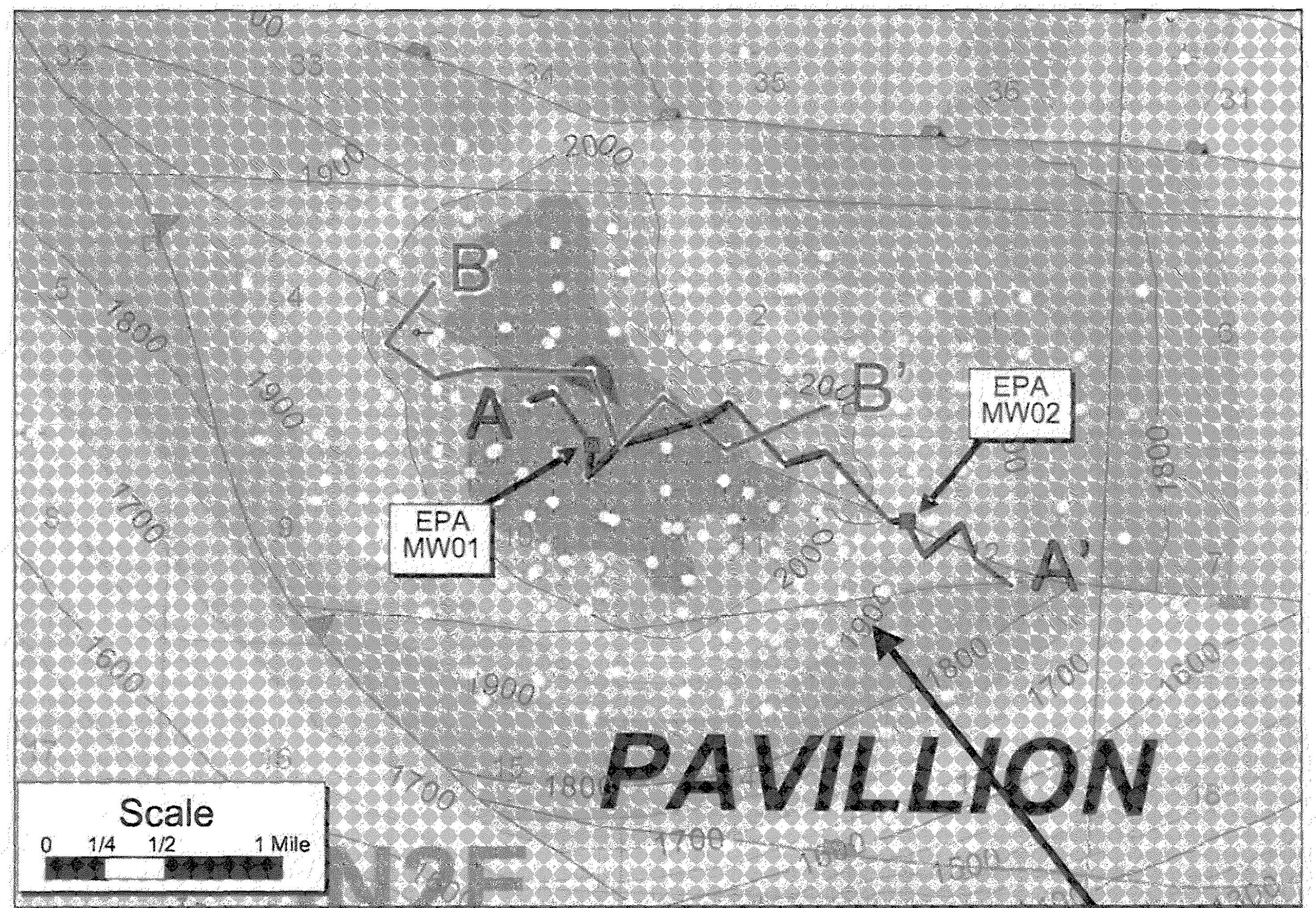
USEPA Figure 20
Cross Section in Core Area

CLIENT: Encana

FIGURE NO. RJS-7

EPAPAV0001396



Elevations in feet above mean sea level - Contour Interval = 50 ft

Approximate View Angle
for Figure RJS-11

Source: Encana

PROJECT NO.	1972
BY	OTHERS/RJS
CHECKED	RJS
DRAWN	OTHERS/SAC
DRAWING NAME	EPA-XSECTION
DRAWING DATE	7 MAR 2012
REVISION DATE	--

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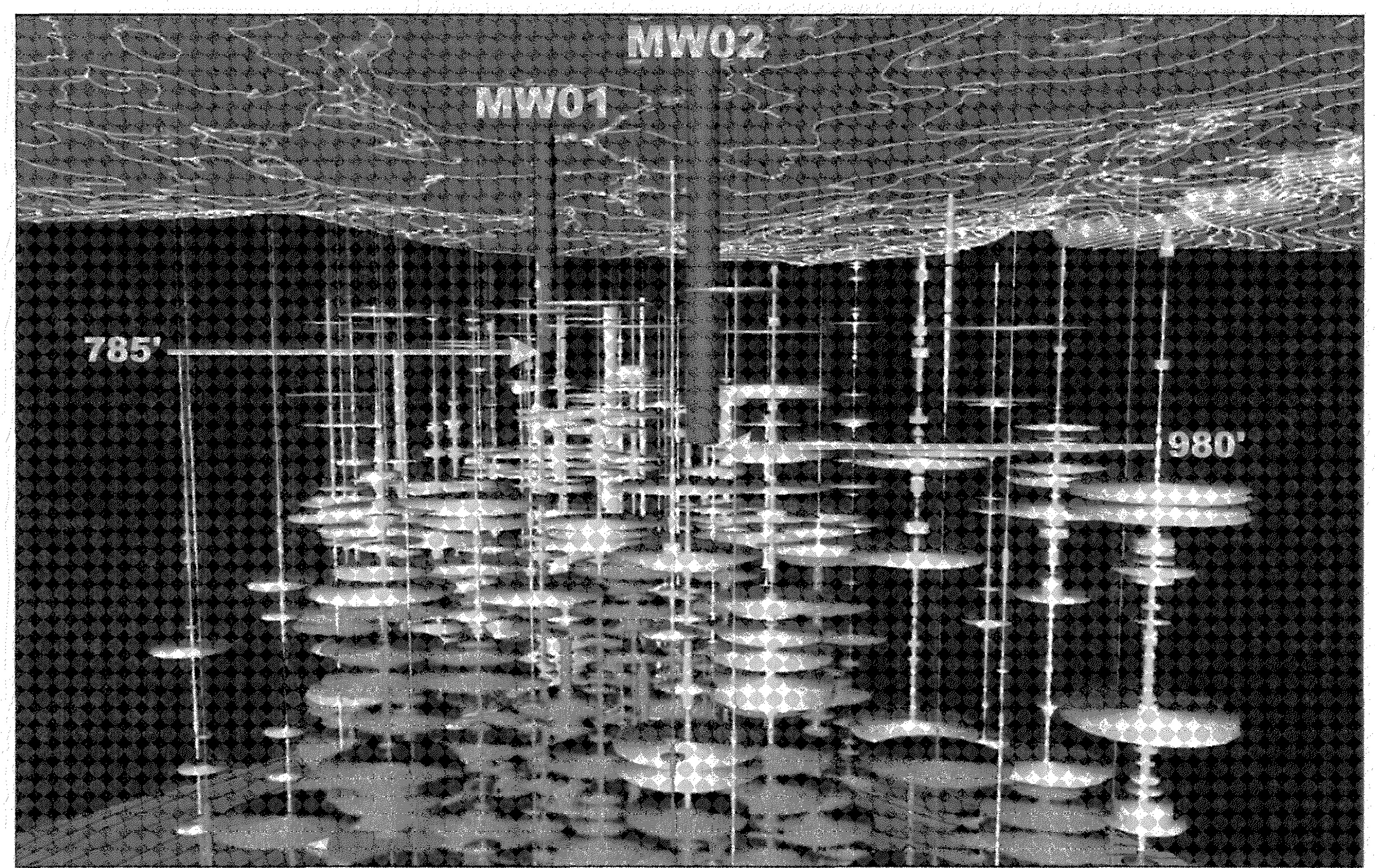
Location of USEPA Cross Section A-A'
with Encana's Cross Section B-B'
and Structural Contour on Top of Fort Union

CLIENT: Encana

FIGURE NO. RJS-8



Source: Encana

Gas Shows (Not Completed)

Gas Shows (Completed)

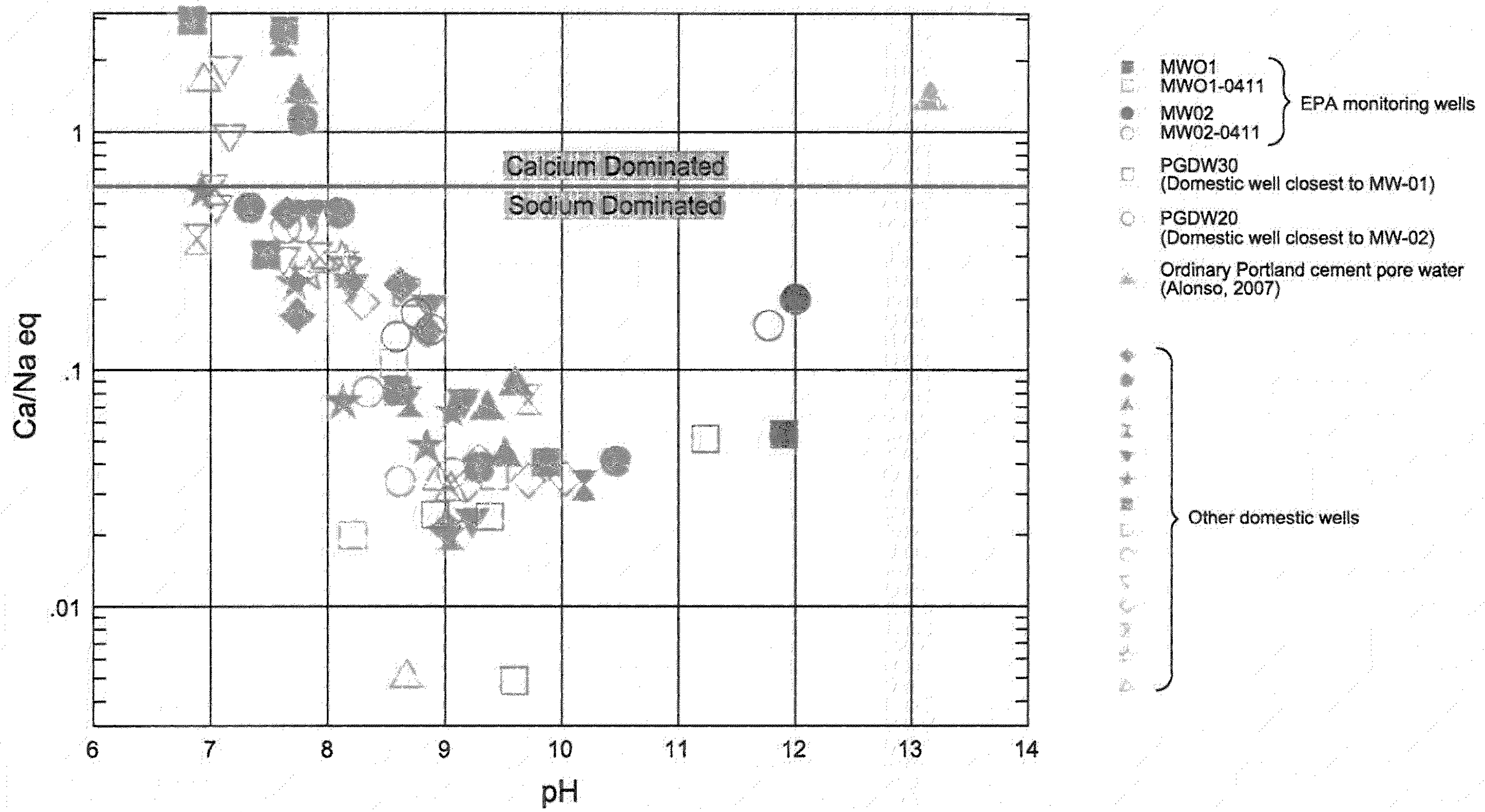
PROJECT NO.	1972
BY	OTHERS/RJS
CHECKED	RJS
DRAWN	OTHERS/SAC
DRAWING NAME	3D-PERSPECTIVE
DRAWING DATE	7 MAR 2012
REVISION DATE	--

ITASCA™ Denver, Inc.

Three-Dimensional Perspective of Pavillion Gas Field Looking Northwest

CLIENT: Encana

FIGURE NO. RJS-11



PROJECT NO.	1972
BY	BTH
CHECKED	RJS
DRAWN	SAC
DRAWING NAME	PH-V-CATONA
DRAWING DATE	7 MAR 2012
REVISION DATE	--

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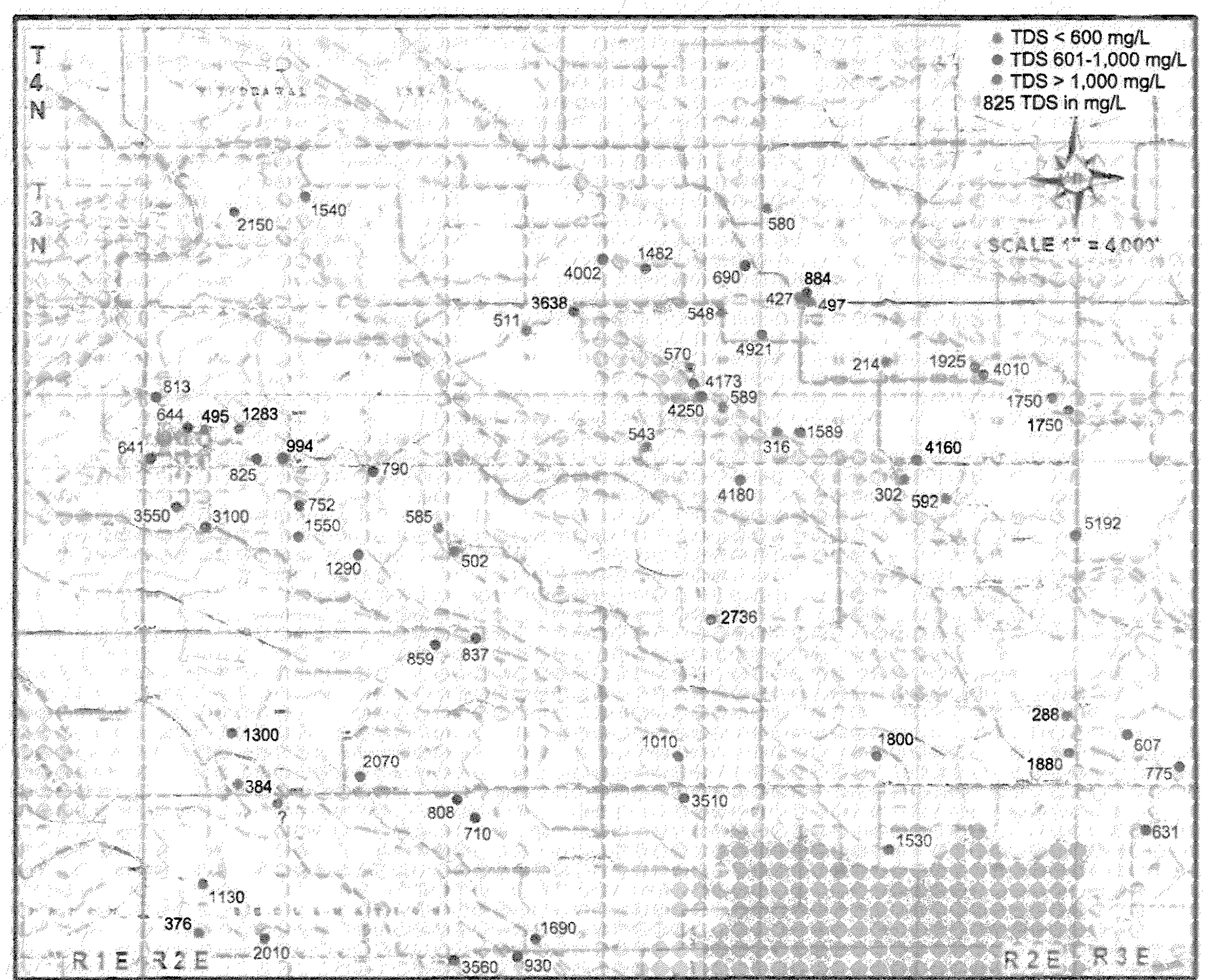
Plot of pH and Ratio of Calcium to Sodium Equivalence in Domestic and Monitoring Wells, and Portland Cement Pore Water

CLIENT: Encana

FIGURE NO. RJS-12



Source: Gores and Associates, 2011

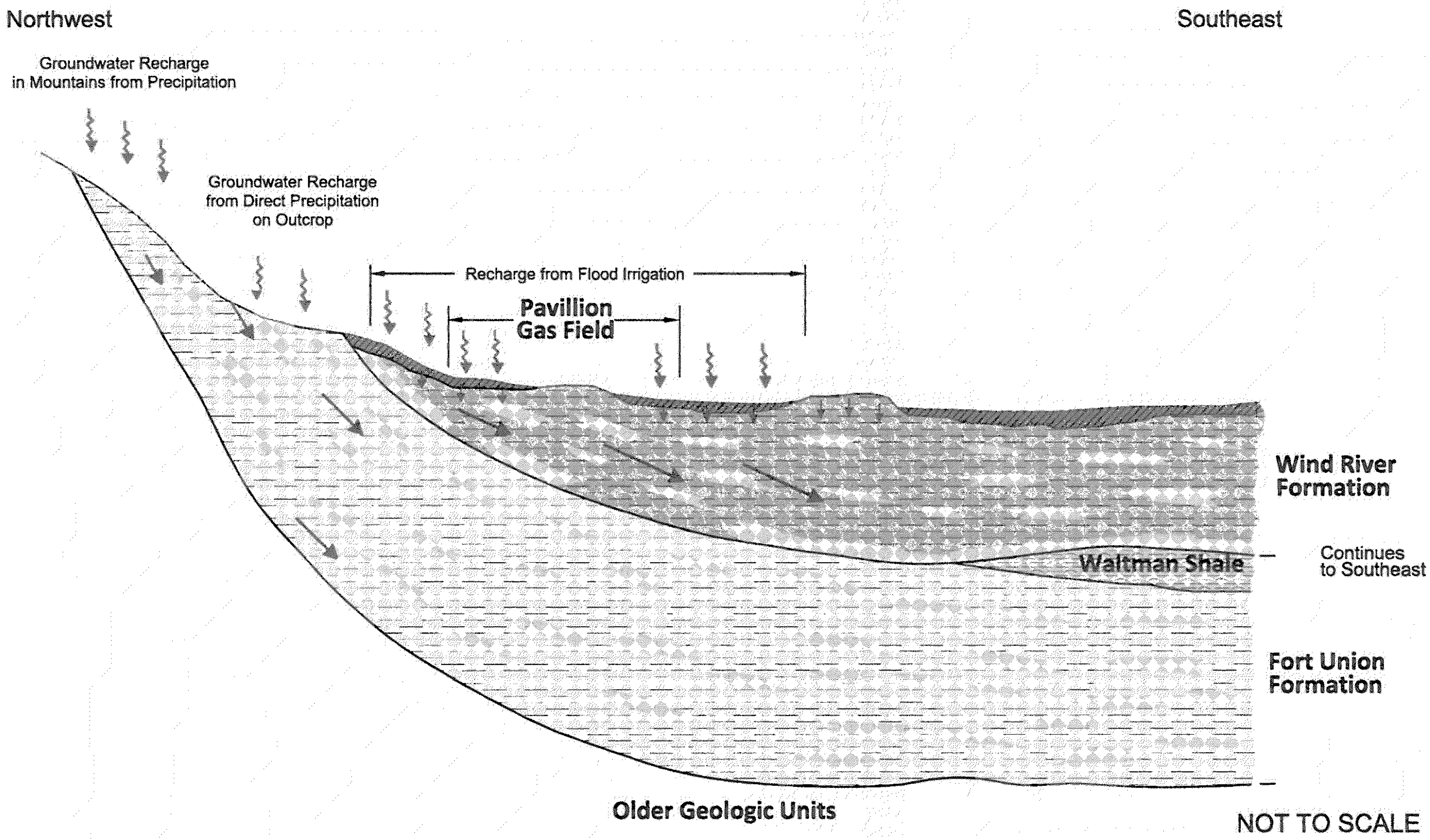
PROJECT NO.	1972
BY	OTHERS
CHECKED	RJS
DRAWN	OTHERS/SAC
DRAWING NAME	TDS-GW
DRAWING DATE	7 MAR 2012
REVISION DATE	--

ITASCA™ Denver, Inc.

TDS of Groundwater in Pavillion Field

CLIENT: Encana

FIGURE NO. RJS-13



EXPLANATION

- SHALE
- QUATERNARY DEPOSITS
- SANDSTONE LENSE
- GROUNDWATER FLOW

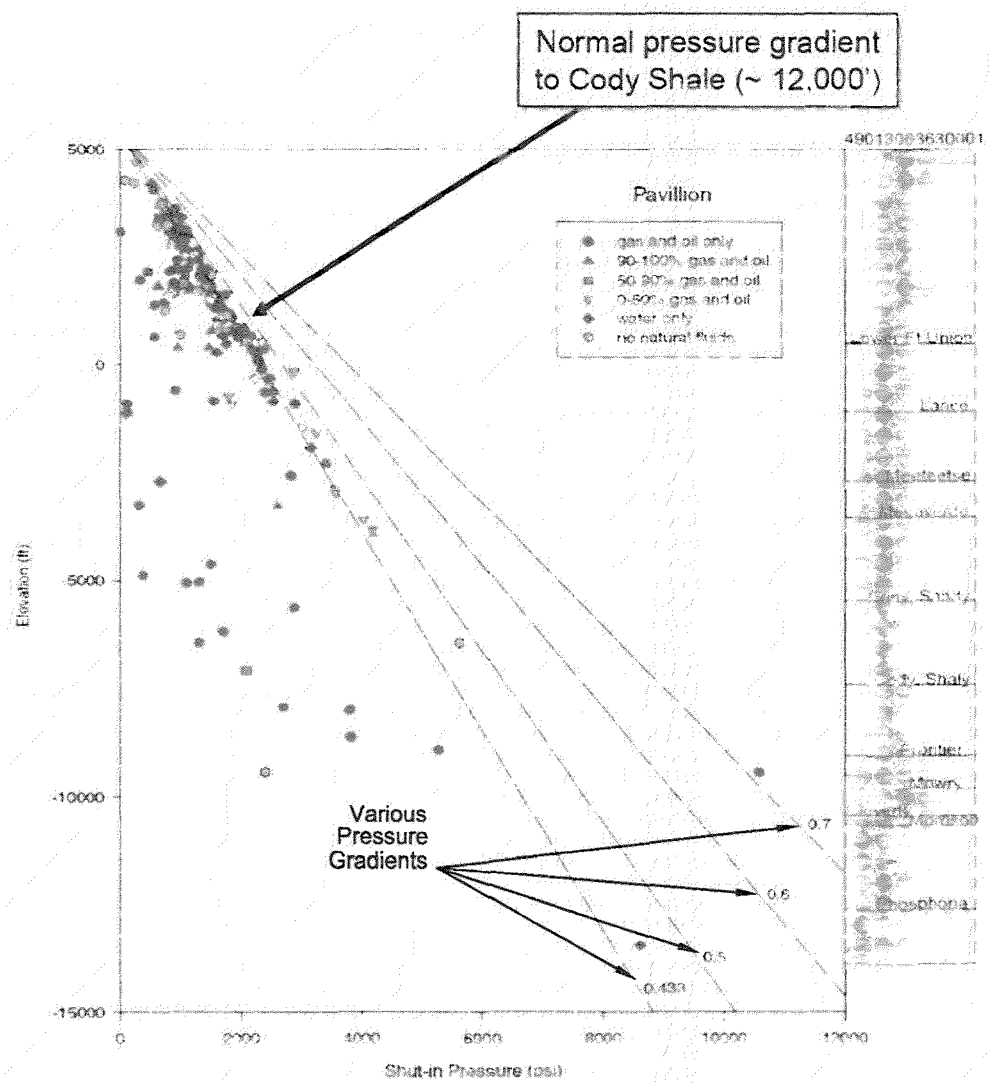
PROJECT NO.	1972
BY	RJS
CHECKED	RJS
DRAWN	SAC
DRAWING NAME	CONCEPTUAL
DRAWING DATE	7 MAR 2012
REVISION DATE	--

ITASCA™ Denver, Inc.

Conceptual Hydrogeologic Model
of Western Wind River Basin
in Vicinity of Pavillion Study Area

CLIENT: Encana

FIGURE NO. RJS-14



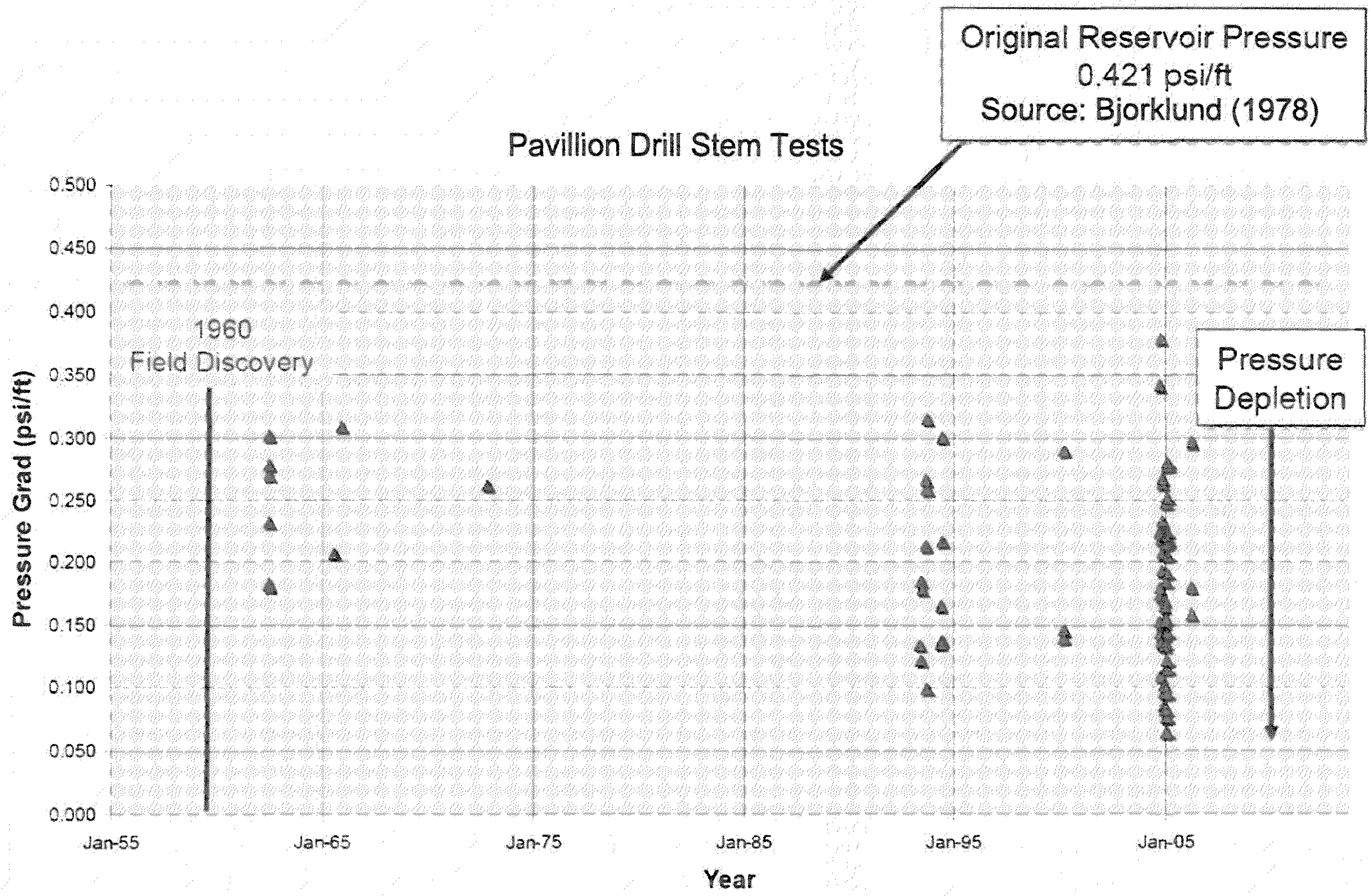
PROJECT NO.	1972
BY	OTHERS/RJS
CHECKED	RJS
DRAWN	OTHERS/SAC
DRAWING NAME	SHUT-IN-PRSR
DRAWING DATE	7 MAR 2012
REVISION DATE	--

ITASCA™ Denver, Inc.

Shut-in Pressures for Various Formations in Pavillion Field (from Encana)

CLIENT: Encana

FIGURE NO. RJS-16



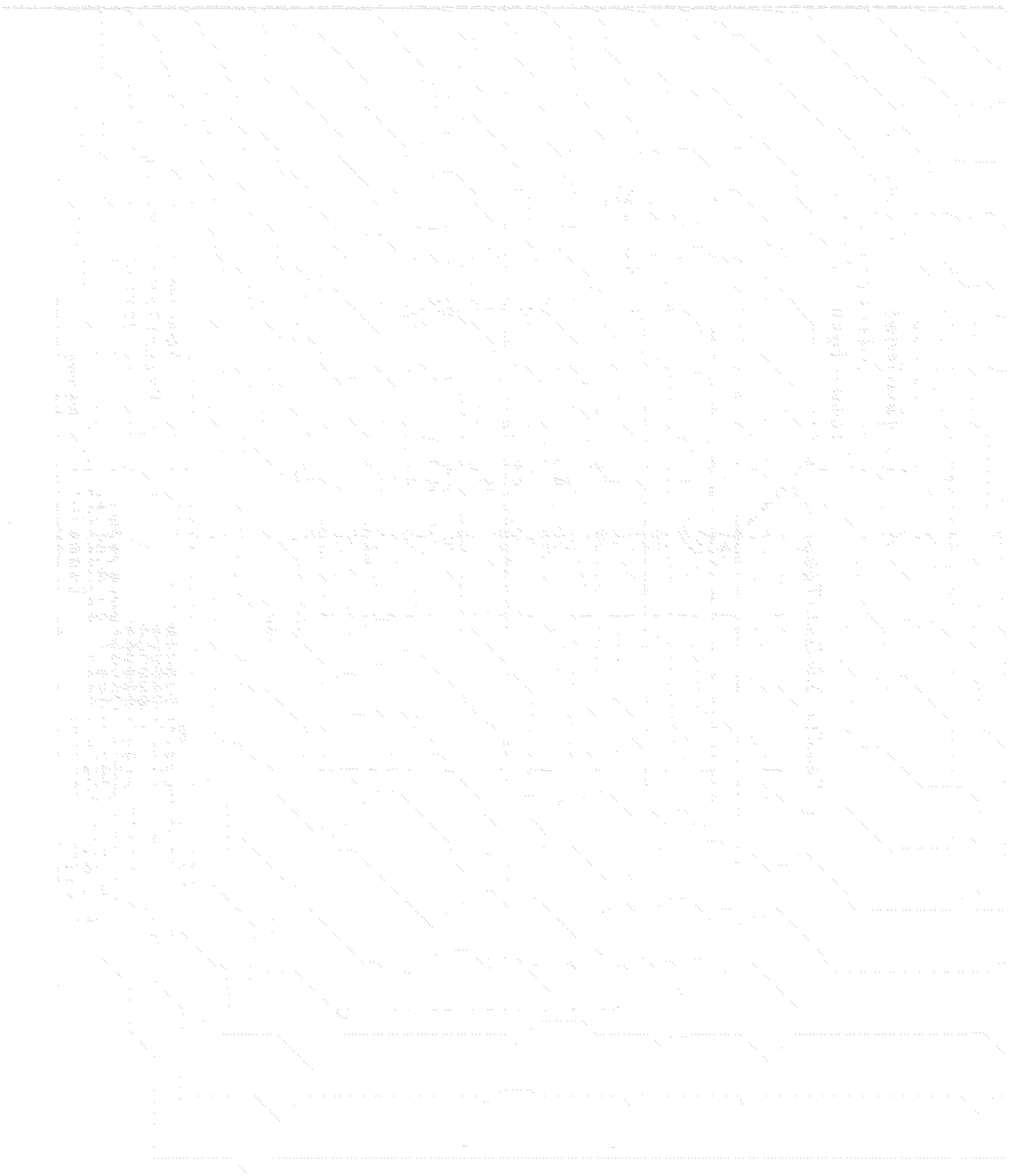
PROJECT NO.	1972
BY	OTHERS/RJS
CHECKED	RJS
DRAWN	OTHERS/SAC
DRAWING NAME	PRESS–TESTS
DRAWING DATE	7 MAR 2012
REVISION DATE	--

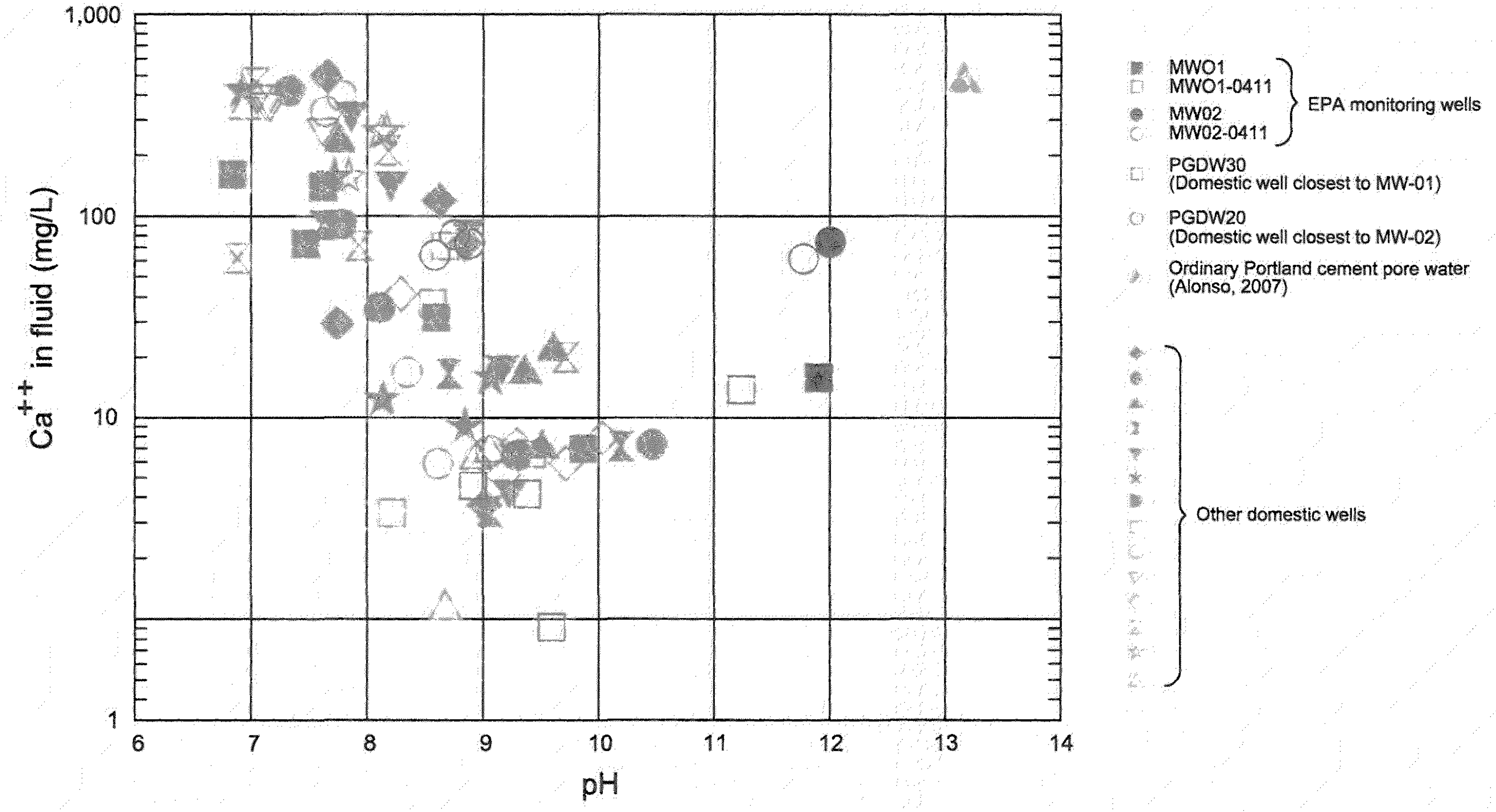
ITASCA™
Denver, Inc.

Wind River Formation
Pressure Tests in Pavillion Field
(from Encana)

CLIENT: Encana

FIGURE NO. RJS-17





PROJECT NO.	1972
BY	BTH
CHECKED	RJS
DRAWN	SAC
DRAWING NAME	PH–V–CA
DRAWING DATE	7 MAR 2012
REVISION DATE	--

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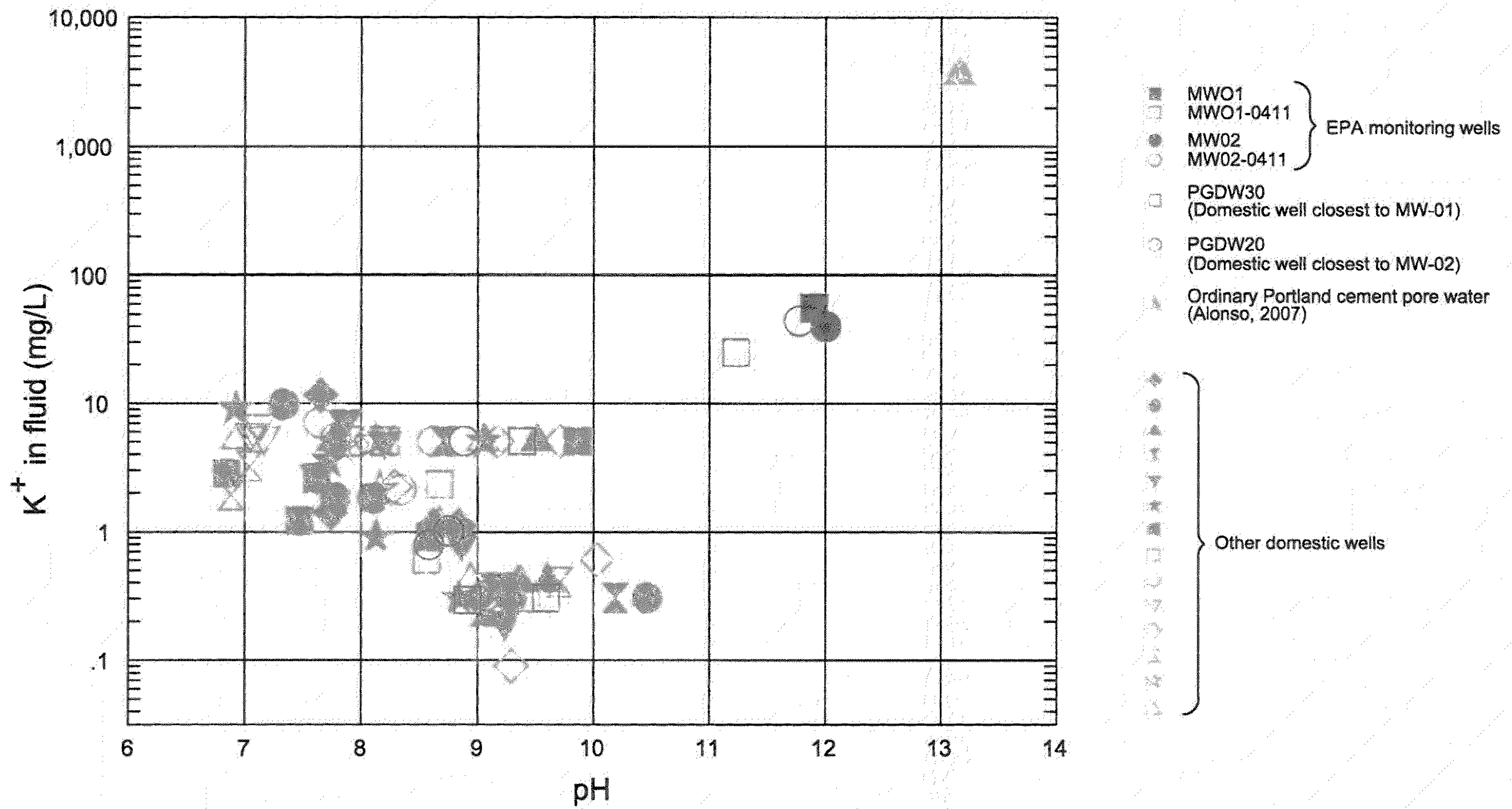
Plot of pH and Calcium (Ca) Concentrations in Domestic and Monitoring Wells, and Portland Cement Pore Water

CLIENT: Encana

FIGURE NO. RJS-21

EPAPAV0001412



PROJECT NO.	1972
BY	BTH
CHECKED	RJS
DRAWN	SAC
DRAWING NAME	PH-V-K
DRAWING DATE	7 MAR 2012
REVISION DATE	---

ITASCA™ Denver, Inc.

Plot of pH and Potassium (K) Concentrations in Domestic and Monitoring Wells, and Portland Cement Pore Water

CLIENT: Encana

FIGURE NO. RJS-22

EPAPAV0001414

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TABLE RJS-1

Geochemical Results for Pavillion Groundwater From USEPA (2011b)
(Page 1 of 2)

Sample ID	T (°C)	pH	Na (ppm)	K (ppm)	Cl (ppm)	SO_4 (ppm)	NO_3 (N) (ppm)	TDS[1] (mg/L)
PGDW01	------	------	808	6.2	34.3	1860	6.2	3347
PGDW02	13.4	8.11	86	1.8	2.6	175	0.25	371
PGDW03	11.1	9.37	272	0.4	25.1	549	0.25	888
PGDW04	11.8	9.17	270	0.4	21.6	551	0.25	880
PGDWOS	12.0	9.02	192	0.3	17	295	0.25	565
PGDWOG	13.8	10.20	249	0.3	31	485	0.25	795
PGDW07	12.4	8.85	213	0.3	15.7	390	0.25	666
PGDW08	12.4	8.57	390	0.6	18.9	857	0.25	1354
PGDW09	12.4	8.35	233	2.1	10.5	279	3.2	703
PGDW10	12.2	8.95	204	0.4	8.0	293	0.25	601
PGDW11	13.1	7.17	423	5.5	15.3	1780	1.3	2856
PGDW12	12.4	10.04	256	0.6	30.8	497	0.25	817
PGDW13	10.9	6.89	196	1.9	6.2	343	1.0	812
PGDW14	10.8	7.85	690	4.5	26.1	1820	0.7	2809
PGDW15	11.4	7.48	269	1.2	9.9	520	1.8	1051
PGDW16	13.2	9.30	188	0.3	13.4	258	0.25	554
PGDW17	12.7	9.61	278	0.4	49.5	583	0.25	947
PGDW18	10.3	8.87	509	0.8	27	1380	0.5	2017
PGDW19	11.8	7.75	194	1.4	6.9	196	2.6	609
PGDW20	9.3	8.76	520	1.0	34.5	1370	0.25	2057
PGDW22	8.3	6.93	837	9.0	79.9	2720	43.6	4431
PGDW23	11.5	9.43	208	0.3	19.8	365	0.25	638
PGDW24	9.7	7.65	938	7.0	55.7	3200	0.25	4759
PGDW25	13.3	8.68	249	1.1	8.4	355	0.25	743
PGDW26	9.2	7.13	220	6.8	14.6	1240	0.25	2106
PGDW28	10.7	8.30	239	2.2	16.7	298	3.7	768
PGDW29	11.5	9.72	298	0.4	52.3	596	0.25	999
PGDW30	10.4	9.60	210	0.3	16.3	331	0.25	617
PGDW31	9.0	8.60	435	0.9	13.3	1030	0.5	1562
PGDW32	9.5	10.47	199	0.3	34.1	373	0.25	637
PGDW33	3.7	7.77	178	5.0	28	670	2.1	1318
PGDW34	8.3	7.87	786	7.4	23	2690	3.5	4172
PGDW35	10.6	8.63	587	1.1	24.1	1610	0.5	2393
PGDW36	9.8	7.62	42	2.6	3.2	195	1.2	503
PGDW37	10.5	8.14	187	0.9	8.7	89.9	1.2	507
PGDW38	9.5	8.68	373	2.3	46.9	908	5.9	1438
PGDW39	6.7	7.79	1110	5.3	52.9	3640	0.6	5421
PGDW40	11.5	9.06	244	5.0	13.1	426	0.15	751
PGDW41	7.2	7.63	1030	2.7	31.4	2670	0.15	4127
PGDW42	12.1	9.18	181	5.0	13.2	311	0.15	575
PGDW43	0.2	8.19	911	5.0	38.4	2470	0.15	3714

TABLE RJS-1

ITASCA Denver, Inc

Geochemical Results for Pavillion Groundwater From USEPA (2011b)
(Page 2 of 2)

Sample ID	T (°C)	pH	Na (ppm)	K (ppm)	Cl (ppm)	SO_4 (ppm)	NO_3 (N) (ppm)	TDS[1] (mg/L)
PGDW44	9.4	8.13	994	5.0	39.5	2880	0.15	4266
PGDW45	9.3	7.63	59	2.6	14.5	213	0.3	688
PGDW46	7.9	7.79	91	1.8	8.4	126	2.3	528
PGDW47	8.2	9.52	183	5.0	21.6	330	0.15	580
PGDW48	8.7	8.21	725	5.0	24.1	1840	0.15	2800
PGDW49	7.8	7.66	1210	11.4	64.3	3160	7.7	5239
PGDW03-0110	8.3	8.71	251	5.0	20.7	570	0.15	886
PGDW04-0110	8.3	9.07	265	5.0	23.3	532	-----	870
PGDWOS-0110	9.4	8.22	188	5.0	16.5	287	0.15	559
PGDW10-0110	10.4	8.62	195	5.0	7.5	293	0.15	601
PGDW20-0110	9.3	8.89	550	5.0	32.6	1270	0.15	1979
PGDW22-0110	8.2	7.06	908	5.8	74.6	2780	40.7	4538
PGDW23-0110	8.2	9.72	194	5.0	19.7	368	0.15	632
PGDW25-0110	7.2	7.94	269	5.0	9.5	441	1.7	983
PGDW30-0110	9.2	9.39	195	5.0	15.5	333	0.15	615
PGDW32-0110	8.3	9.87	193	5.0	21.4	368	0.15	621
MW01	11.8	11.91	334	54.9	23.3	398	0.15	1086
MW02	12.3	12.01	420	39.5	466	12.1	0.38	1286
RD01	11.5	9.24	208	0.2	15.2	357	0.23	633
LD01	10.9	8.85	562	1.1	33.0	1320	0.35	2030
PGDWOS-0411	10.5	9.06	190	0.24	16.8	276	0.15	536
PGDW14-0411	8.5	7.73	753	3.52	23.7	1760	0.36	2807
PGDW20-0411	8.3	8.59	520	0.78	22.9	1150	0.15	1826
PGDW23-0411	11.0	9.07	208	0.31	19.9	365	0.15	645
PGDW26-0411	8.3	6.95	232	5.15	13.2	1180	1.37	1940
PGDW30-0411	10.4	8.92	210	0.29	16.1	327	0.15	608
PGDW32-0411	11.1	9.30	198	0.09	18.8	361	0.15	615
PGDW41-0411	8.2	7.05	896	3.18	97.6	2640	17.5	4220
PGDW44-0411	10.0	8.17	1060	2.09	32.1	2900	0.15	4329
PGDW45-0411	9.1	6.85	61.6	2.81	18.4	251	0.64	748
PGDW49-0411	10.4	7.34	982	9.66	54.3	3200	8.75	4976
MW01-0411	11.2	11.24	304	24.7	23.1	339	0.15	939
MW02-0411	12.0	11.78	448	43.6	457	63	0.15	1363
Maximum	13.8	12.01	1210	54.90	466.0	3640	43.60	5421
Minimum	0.2	6.85	42	0.09	2.6	12	0.15	371
Average	10	9	405	5	37	991	2	1674

Note: [1] TDS calculated using the methodology published by Csuros (1997).

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TABLE RJS-2

Pavillion Area Wells - Groundwater Quality Data by Gores and Associates (2011)

	Permit #	Twnshp	Rng	Sect.	Qtrqtr	Well Depth	Ground Elevation	Chemical Data Source	TDS (mg/l)	Cond (µmho/cm)	Sodium (mg/l)	Sulfate (mg/l)
1		3	2	2	SE SW			WRDS Has Chemical Analysis	884	1340	210	860
2		3	2	2	SW NW			WRDS Has Chemical Analysis	580			300
3	P170310W	3	2	2	SWSW		5356	EPA Well No. PGDW45	427		59	213
4	PGDW05	3	2	2	SWSW		5355	EPA Well No. PGDW05	497		189	287
5	P66345W	3	2	3	NWSW	70	5397	EPA Well No. PGDW41	4002		1030	2670
6	P98084W	3	2	3	SESE		5374	EPA Well No. PGDW40 ???	690		244	426
7	PGMW01	3	2	3	SESW		5393	EPA Well No. PGMW01	1482		128	1010
8		3	2	5	SW NW			WRDS Has Chemical Analysis	1540	2180	459	990
9	P14914P	3	2	6	SWNE	130		WRDS Has Chemical Analysis ????	2150	2810	362	945
10	P98757W	3	2	7	NWSW	517	5479	Sampled by Wester-Wetstein on 2-18-11	813	1261	255	439
11		3	2	7	SE SE			WRDS Has Chemical Analysis	994	1400	203	480
12	P58929W	3	2	7	SESE	57	5420	WRDS Has Chemical Analysis ????	825	1250		
13	P70972W	3	2	7	SESW	506	5466	EPA Well No. PGPW01	495		173	300
14	P34345W	3	2	7	SESW	510	5472	WRDS Has Chemical Analysis	680		190	400
15	P59104W	3	2	7	SESW	510	5472	WRDS Has Chemical Analysis	644		210	460
16		3	2	7	SW SW	380		WRDS Has Chemical Analysis	647	974	210	345
17	P76991W	3	2	7	SWSE	515	5446	EPA Well No. PGPW02	1283		393	847
18	PGDW43	3	2	9	NENE		5397	EPA Well No. PGDW43	3628		911	2470
19	P41517W	3	2	9	NENW	200	5400	EPA Well No. PGDW42	511		181	311
20	PGDW30	3	2	10	NENE		5371	EPA Well No. PGDW30	548		195	333
21	P24507P	3	2	10	NWSE	750	5404	WRDS Has Chemical Analysis	4250			2900
22	P24508P	3	2	10	NESE	175	5436	EPA Well No. PGDW23	589		194	368
23	P124049W	3	2	10	SESW	484	5385	EPA Well No. PGDW47	543		183	330
24		3	2	10	SW NE			WRDS Has Chemical Analysis	570	913	174	320
25	PGDW44	3	2	10	SWNE		5399	EPA Well No. PGDW44	4173		994	2880
26	PGDW49	3	2	11	NWNW		5373	EPA Well No. PGDW49	4921		1210	3160
27	PGMW03	3	2	11	SENE		5351	EPA Well No. PGMW03	214		27	28
28	P51810W	3	2	11	SESE		5338	EPA Well No. PGDW22 ???	4160		908	2780
29	PGDW46	3	2	11	SWSW		5377	EPA Well No. PGDW46	316		91	126
30	PGMW02	3	2	11	SWSW		5364	EPA Well No. PGMW02	1589		1020	108
31		3	2	12	NE SE			WRDS Has Chemical Analysis	1750		447	1110
32		3	2	12	NE SE			WRDS Has Chemical Analysis	1750		447	979
33	P97501W	3	2	12	SENW		5328	SEO	4010		555	1161
34	PGDW20	3	2	12	SENW		5328	EPA Well No. PGDW20	1925		550	1270
35	P64110W	3	2	13	NWNW	675	5331	EPA Well No. PGDW32	592		193	368
36	P42890W	3	2	13	SENE	57	5300	WRDS Has Chemical Analysis (EPA Well No. PGDW39)	5192		1110	3640
37		3	2	14	NE NE			WRDS Has Chemical Analysis	302	457	38	67
38	P30217W	3	2	15	NENE	350		WRDS Has Chemical Analysis	4180			2700
39	PGDW48	3	2	15	SWSE		5358	EPA Well No. PGDW48	2736		725	1840
40	P183732W	3	2	16	NWSW	740	5360	Sampled by Wester-Wetstein on 1-12-11 (EPA Well No. PGDW10)	502	934	195	293
41		3	2	17	NE SW			WRDS Has Chemical Analysis	1290			827
42	P101483W	3	2	17	NWNE	80	5393	EPA Well No. PGDW25 ???	790		269	441
43	P182983W	3	2	17	SENE	760	5376	Sampled by Wester-Wetstein on 1-12-11	585	886		
44		3	2	17	SW NW			WRDS Has Chemical Analysis	752	1140		
45	P46362W	3	2	17	SWNW	220	5388	WRDS Has Chemical Analysis	1550		140	1100
46	P62641W	3	2	18	NENW	705	5455	WRDS Has Chemical Analysis	3550		970	2200
47		3	2	18	SE NW			WRDS Has Chemical Analysis	3100			2140
48		3	2	19	NW SE			WRDS Has Chemical Analysis	1300			642
49	P53567W	3	2	19	SWSE	140	5420	WRDS Has Chemical Analysis	384		175	84
50	P120203W	3	2	20	NENE	450	5347	EPA Well No. PGDW03	859		251	570
51	P25636W	3	2	20	SESW	41	5360	WRDS Has Chemical Analysis	2070			750
52	P168584W	3	2	21	NWNW	440	5375	EPA Well No. PGDW04	837		265	532
53	P110443W	3	2	22	SESW	420	5360	Ow ner Furnished - This Study	1010	1539	298	570
54		3	2	23	SE SE			WRDS Has Chemical Analysis	1800		454	620
55	P28496W	3	2	24	NESE	65	5293	SEO	288			29
56	P26200W	3	2	24	SESE	740	5260	WRDS Has Chemical Analysis	3880			2610
57		3	2	26	SE NE			WRDS Has Chemical Analysis	1530	2160	445	988
58		3	2	27	NE NW			WRDS Has Chemical Analysis	3510	3790	339	2310
59	P40603W	3	2	28	NWNW	40	5312	WRDS Has Chemical Analysis	710			210
60	P76475W	3	2	28	NWNW	320	5320	SEO	808	1320	260	540
61	P14548P	3	2	28	SWSE	60	5300	WRDS Has Chemical Analysis	1690			1049
62	P30162W	3	2	30	NENE	200	5400	WRDS Has Chemical Analysis				169
63	P32163W	3	2	30	NESW	425	5380	WRDS Has Chemical Analysis	1130			690
64	P9441P	3	2	30	SESE	582	5371	WRDS Has Chemical Analysis ????	2040	2720	579	1290
65	P116598W	3	2	30	SESW	470	5347	SEO	376		229	119
66		3	2	33	NE NW			WRDS Has Chemical Analysis	930			296
67	P25011W	3	2	33	NWNW	300	5340	WRDS Has Chemical Analysis	3560			2400
68	P177246W	3	3	19	SWSE	1000	5287	Sampled by Wester-Wetstein on 1-12-11	775	1180	248	457
	P177246W	3	3	19	SWSE	1000	5287	Sampled by Wester-Wetstein on 1-12-11	590	1180	126	237
69	P190223W	3	3	19	SWSW	1055	5309	Sampled by Wester-Wetstein on 1-12-11	607	920		
70	P191733W	3	3	30	SENW	900	5272	Sampled by Wester-Wetstein on 1-12-11	631	956		
								Maximum Value	5192	3790	1210	3640
								Minimum Value	214	457	27	28
								Average	1579	1491	386	976

TABLE RJS-3

Data for Figure 15

(Page 1 of 2)

Ground-Water Resources of Riverton Irrigation Project Area, Wyoming. Geological Survey Water-Supply Paper 1375

Morris, Hackett, Vanlier, and Moulder. 1959

Tables 16-18

Well ID	Location within A3N-2E	Well Depth (ft)	Land Surface Elevation (ft)	Water Level (BGS) (ft)	Water Elevation (ft)
N/A	2cd	205	5338	156	5182
N/A	2dd	108	5338	38	5300
N/A	9ab	30	5392	18	5374
N/A	10cd1	65	5375	38	5337
N/A	10db2	482	5405	15	5390
N/A	11ba	70			
N/A	11bb	60	5360	21	5339
N/A	11cb	99	5357	11	5346
N/A	11dc	92	5384	155	5229
N/A	12bb	280	5349	19	5330
N/A	12bd1	65	5323	40	5283
N/A	12bd2	132	5322	40	5282
N/A	12cc	97	5324	113	5211
N/A	12dc	449	5311	14	5297

Water Resources of Freemont County, Wyoming. USGS Water-Resources Investigations Report 95-4095

Plafcan, M., C. A. Eddy-Miller, G. F. Ritz and J. P.R. Holland II. 1995

Tables 11 & 16

Well ID	Location within A3N-2E	Well Depth (ft)	Land Surface Elevation (ft)	Water Level (BGS) (ft)	Water Elevation (ft)
N/A	2cdc	47	5352	9	5343

"Ground-Water Resources of Wind River Indian Reservation, Wyoming" Water Supply of Indian Reservations

McGreevy, Hodson, and Rucker. 1969

Table 3

Well ID	Location within A3N-2E	Well Depth (ft)	Land Surface Elevation (ft)	Water Level (BGS) (ft)	Water Elevation (ft)
N/A	3bdb	238	5390	155	5375

Spreadsheet of Well Permit Information, State Water Engineer

Well ID	Location within A3N-2E	Well Depth (ft)	*Land Surface Elevation (ft)	Water Level (BGS) (ft)	Water Elevation (ft)
P164192.0W	1bd	80	5420	60	5360
P164193.0W	1ca	100	5401	82	5319
P164194.0W	1db	103	5401	81	5320
P123668.0W	2bb	60	5370	12	5358
P89840.0W	3ad	215	5395	20	5375
P66345.0W	3bc	70	5391	7	5384
P41517.0W	9ab	200	5397	50	5347
P124049.0W	10dc	484	5378	246	5132
P24506.0P	10bd	750	5453	90	5363
P24507.0P	10bd	750	5453	80	5373
P24508.0P	10ad	175	5375	80	5295
P31805.0W	11dc	100	5359	50	5309
P69549.0W	11dc	100	5359	45	5314

* Estimated based on map location

ITASCA Denver, Inc.

TABLE RJS-3
Data for Figure 15
(Page 2 of 2)

Public and Private Well Depth Information - Pavillion Study Area

Well ID	Location within A3N-2E	Well Depth (ft)
PGDW20	12bd	460
PGDW23	10da	500
PGDW30	10aa	260
PGDW 40	3da	220
PGDW41	3cb	376
PGDW44	10db	750
PGDW45	2cc	100
PGDW46	11cc	48
PGDW47	10cd	500
PGDW49	11bb	50

Wells from Map File

Well ID	Location within A3N-2E
PGDW09	2bb
PGDW14	10ac
PGDW24	2dd
PGDW21	12bd
PGDW22	12cc
PGDW26	11bb
PGDW36	2dd
PGFM20	12cc

ATTACHMENT RJS-1

Résumé for
Robert J. Sterrett, Ph.D.

Robert J. Sterrett

ITASCA

Principal Hydrogeologist

Expertise	Hydrogeology, Engineering Geology
Education	Ph.D. (Engineering Geology), 1980, University of Wisconsin, Madison M.S. (Geology and Geophysics, emphasis on Hydrogeology), 1975 M.S. (Water Resources Management), 1974 B.S. (Geology, with Honors), 1972, Indiana University, Bloomington
Registrations	Professional Geologist – Wyoming Geologist – California Environmental Manager – Nevada
Professional Societies	Association of Ground-Water Scientist & Engineers Geological Society of America (Executive Committee of the GSA Foundation)

Professional Experience

2008 – Present	*Itasca Denver, Inc., (formerly Hydrologic Consultants, Inc.), Colorado* *Principal Hydrogeologist, General Manager*
2002 – 2008	*Engineering Management Support Inc, Colorado,* *(EMSI is a partnership of 4 partners)* *Principal Hydrogeologist*
1999 – 2002	*RJS Consulting, Inc., Colorado* *Independent Consulting Hydrogeologist, Engineering Geologist*
1989 – 1999	*Hydrologic Consultants, Inc. of Colorado* *Co-Founder, Vice President, Principal Hydrogeologist*
1974 – 1989	*Various positions as a Hydrogeologist in academic and consulting firms*

Project Experience

Dr. Sterrett has over 30 years of experience in the field of hydrogeology. Over the past several years, he has been working on water-related issues dealing with open pits, underground mines, and oil and gas operations. This work has involved assessing volumes of water to be pumped from mines, sources of water to mines, and modeling of heap-leach operations. Dr. Sterrett conducted field investigations of large mine waste-rock piles for the purpose of proposing alternative management strategies that would minimize the amount of acid rock drainage that may be produced. In addition, Dr. Sterrett has worked on dewatering projects associated with large civil projects such as dewatering of foundations for large waste-water treatment plants and water supply for electrical power generation plants. Dr. Sterrett has worked on impacts of produced water on groundwater quality, assessment of sources of methane in groundwater, and potential impacts to groundwater quality as a result of oil and gas development.

Dr. Sterrett has extensive experience regarding the fate and transport of chemicals in soil and groundwater. He has worked extensively in the area of the movement of fluids in the vadose zone and on multi-phase fluid issues as well as the movement of fluids through fractures. He has participated in and has directed projects involving site assessment, quantitative analysis of fate and transport in groundwater, and the design, implementation, and evaluation of waste remediation technologies in both the saturated and unsaturated zones.

He is the technical editor and a contributor to the Third Edition of ***Groundwater and Wells***, a standard reference in the hydrogeology field.

Teaching: Dr. Sterrett has taught courses in hydrogeology, geologic engineering and contaminant transport at the Colorado State University (Fort Collins, CO), the Colorado School of Mines (Golden, CO), the University of California (Davis, CA), and the University of Santiago (Chile).

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